Satellite Thruster Propulsion: H2O2 Bipropellant Comparison with Existing Alternatives

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Abstract: At the Institute of Aviation the small rocket division has been developing a green alternative for chemical bi-propellant thrusters. The 200N-250N HTP/Isooctane propellant thruster has a theatrical specific impulse of 266s at the ideal MR of 6.5. A comparison of alternative green propellants was undertaken to analyze where an HTP system could be best utilized. Propulsion systems ranging from 1 mN to close to 1 kN were considered in the evaluation of current satellite systems. Analysis trends in different orbital satellites were completed in terms of satellite mass, altitude, and thrust. Analyses displayed that for a 500 N HTP/Isooctane thruster a satellite best fit to house the propulsion system would resemble the GEO satellite the *Hot Bird 6* on the *Spacebus-3000B3* platform.

Introduction

Toxic, unstable propellants have been the standard means of spacecraft propulsion due to their highly reactive characteristics. However, most propellants used in space programs pose environmental concerns in four main areas: ground-based impacts, atmospheric impacts, space-based impacts, and biological impacts [6]. High cost and risk arise with such environmental impacts, therefore mitigating them remains to be a high priority to space system developers. The challenge has been analyzing the cost of using highly toxic propellants that generate environmental pollutants compared to the cost of developing and qualifying green alternatives. Simpler designs for green propulsion systems could avoid this bottleneck during development [6].

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March 2014

Propulsion Systems

Today, several methods of spacecraft propulsion are in use or being developed including chemical, solar, nuclear, and electric powered systems. The most commonly practiced method of propulsion is through the use of chemical propellants, both in liquid and solid states. Ever since the containment of liquid oxygen (LOX) and liquid hydrogen (LH_2) in the late 1800's, scientists have been researching the use of liquid propellants for rocket propulsion. On March 16, 1926, Robert H. Goddard launched the first liquid propellant rocket, powered by LOX and gasoline. Since then over 170 liquid propellants have been lab tested. The most commonly used propellants are LOX, LH_2, RP-1(or its foreign equivalents), MMH, UDMH, hydrazine, nitrogen tetroxide (NTO), and MON. The performance parameters for rockets are their specific impulse, I_{sp}, thrust, and propellant density. Oxygen/hydrogen is the highest performing operational propellant family, with I_{sp} of 391 s [7].The cryogenic, high performance nature of LOX/LH_2 and LOX/RP-1 make them ideal for main stage and upper stage boosters, yet the relative low density and unstable characteristics make them undesirable for long term mission applications.

The bi-propellant combination of nitrogen tetroxide/MON and hydrazine/UDMH/MMH is considered the standard propellant mixture for deep space propulsion, orbital maneuvers, and even reaction control systems on larger satellites, such as Galaxy 17 communications satellite. The Galaxy 17 uses Astrium's 400 N S400 model apogee kick motor as well as Astrium's 10 N bipropellant thrusters, both of which are fueled by MMH/hydrazine bipropellant systems [8]. These storable propellants are ideal for such applications since they remain stable for long term missions.

Hydrazine, and its derivatives MMH and UDMH, is a multipurpose propellant that can be used as a hypergolic bipropellant with nitrogen tetroxide for maneuvering propulsion [23] or in a monopropellant thruster with a catalyst, for station keeping propulsion [23][6].Toxic effects of hydrazine include conjunctivitis, pulmonary edema, anemia (hemolytic), ataxia, convulsions, kidney toxicity, and liver toxicity [16]. Due to its high toxicity, hydrazine alternatives are being developed by space propulsion companies. The Swedish company ECAPS developed a satellite thruster based on an aqueous ADN solution. The propellant LMP-103S is a storable Ammonium Dinitramide (ADN) based premixed bipropellant that demonstrates a density impulse of up to 30% higher than monopropellant hydrazine [1].The HPGP (high performance green propellant) 1N thrusters were used on the formation-flying PRISMA LEO satellites for rendezvous maneuvers with the capability of providing a 60 m/s delta-v [1]. ECAPS is currently developing 5 N and 22 N versions of the HPGP rocket engine with future development plans for 50 N and 220 N versions.

Monopropellants contain an oxidizing agent and combustible matter in a single substance and are commonly used for reaction control systems, such as the 20 N altitude control thrusters used on the LRO's secondary propulsion system [13].Typical monopropellant systems use hydrogen peroxide or hydrazine. In the past, hydrogen peroxide was used for satellite propulsion, but research has slowed since improved catalysts for hydrazine thrusters became available [6].However for the last decade, General Kinetics has offered 3-, 6-, and 25-pound force propellant systems based on hydrogen peroxide [6].

Electric propulsion offers another potential green alternative with new research in systems such as arcjets, resistojets, ion thrusters, and Hall Effect thrusters. Electric Propulsion devices have traditionally been used for station keeping and disposal maneuvers*. Due to their low thrust applications, EP systems remain to be a challenge for space system developers to integrate into main propulsion systems. As a result some satellite developers still use chemical thrusters to provide some of the velocity increments in orbital control systems [6].Launched in 2003, the European lunar orbiter, the SMART-1, supported a similar configuration. Xenon propellant was used to power the main engine, a SNECMA PPS-1350G plasma hall thruster, which provided 0.068 N of thrust as well as a specific impulse of 1640 s*. The lunar orbiter was also equipped with eight 1 N hydrazine monopropellant thrusters to handle altitude control during lunar orbit insertion [13]. Aerojet Rocketdyne has recently developed the XR-12 Hall Current Thruster which provides significantly improved specific impulse and flexibility over conventional chemical propulsion systems, with thrust levels up to 0.815 N and specific impulses as high as 2208 s*. The Hall thruster system was developed to satisfy both orbit transfer and on-orbit station keeping propulsion needs of large communications satellites [26]. Similar to the SMART-1 and the XR-12, the Surrey SSTL-150 is propelled by xenon; however it supports a resistojet for its station keeping and orbit maintenance operations [5]. In 2015 Boeing plans to launch the first all-electric satellite propulsion system the 702SP. Boeing has had previous success with its high efficient hybrid bipropellant and XIP propelled satellite, the 702HP.

Although current technologies exist for green replacement propellants in small thrusters, such replacements have yet to be seen in high thrust applications. In an attempt to understand where a “green” high thrust bipropellant system would be best utilized, a standard of propulsion systems was established. The combination of propulsion systems was compiled to obtain a reference in the evaluation of the relationship between different parameters of a satellite system. Thrusts varying from below 1 mN to close to 700 N are demonstrated in Table 1& 2.

Table 1 - Summary of Propulsion Systems *Part A*

Spacecraft	Propulsion system	Propulsion Type	Propellants	Type	Functions	Thrust [N]	I_{sp} [s]
MESSENGER (2004)	LEROS-1b	Bi-propellant	MON/Hydrazine	Deep Space	Deep Space Trajectory Correction/ Planetary Orbit Insertion	645	317
Chang' E-2 (2010)	Chang' E-2	Bi-propellant	MON-1/MMH	GTO to Lunar Orbiter	Orbit Raising	490	312
TDRS-L (2014)	R-4D-11-300	Bi-propellant	N_2O_4/MMH	Geostationary	Orbit Insertion	490	312
Astra 1KR (2006)	LEROS-1C	Bi-propellant	MON/Hydrazine	Geostationary	Orbit Insertion	458	324
AEHF (2010)	Liquid Apogee Engine	Bi-propellant	N_2O_4/Hydrazine	Geostationary	Orbit Insertion	440	340
Galaxy 17 (2007)	Airbus Model S400-12	Bi-propellant	MMH/Hydrazine	Geostationary/ Deep Space Probes	Orbit Injection/ Orbit Manoeuvers	420	318
N./A	Bi-propellant System	Bi-propellant	H_2O_2/Isooctane	N/A	N/A	220	266
Julius Verne ATV-001 (2008)	Astrium 200 N Bi-propellant Thruster	Bi-propellant	N_2O_4+MON-1,3/MMH	Rendezvous	Altitude Control/Braking Thrusters	216	270
OSIRIS-Rex (2016)	Astrium 200N Thrusters	Bi-propellant	N_2O_4/MMH	Asteroid Retrieval Mission	Reaction Control System	200	287
LRO (2009)	LRO	Mono-propellant	Hydrazine	Lunar Orbiter	Lunar Insertion	88	205
AEHF (2010)	Secondary Thrusters	Mono-propellant	Hydrazine	Geostationary	Orbit/Altitude Maintenance	23	225
Galaxy 17 (2007)	Astrium10 N Bi-propellant Thruster	Bi-propellant	MMH/Hydrazine	Large Satellites/Deep Space Probes	Altitude, Trajectory and Orbit Control	10	291
-	Astrium 1 N Mono-propellant Thruster	Mono-propellant	Hydrazine	Small Satellites/Deep Space Probes	Altitude, Trajectory and Orbit Control	1	220
OSIRIS-Rex (2016)	1N Hall Thrusters	Hall Effect Thruster	Xenon	Asteroid Retrieval Mission	Altitude Control	1	3,000
PRISMA (2010)	HPGP 1 N Rocket Engine	Mono-propellant	LMP-103S (ADN)	Science Research/ Deep Space	Autonomous Formation Flying and Rendezvous Maneuvers	1	235

SMART-1 (2003)	SMART-1 (Reaction Control System)	Mono-propellant	Hydrazine	Lunar Orbiter	Altitude, Trajectory, and Orbital Control	1	220
AEHF (2010)	Altitude thrusters	Mono-propellant	Hydrazine	Geostationary	Orientation Control	0.9000	225
Future Systems	Aerojet Rocketdyne XR-12	Hall Effect Thruster	Xenon	Geostationary	Orbit Transfer/Station keeping	0.8150	2,208
AEHF (2010)	Aerojet Rocketdyne XR-5	Hall Effect Thruster	Xenon	Geostationary	Station keeping/Orbit Maintenance	0.2270	2,000
Multiple	Boeing 702HP	Ion Thruster	Xenon	Geostationary	Station keeping/Orbit Maintenance	0.1650	3,500
SMART-1 (2003)	SNECMA PPS-1350G	Plasma Hall Effect Thruster	Xenon	Lunar Orbiter	Orbit Injection/ Orbit Manoeuvers	0.0680	1,540
ESA: Porba-2 (2009)	Surrey SSTL-150	Resistojet	Xenon	Geocentric	Station keeping/Orbit Maintenance	0.0180	48
CMT (2003)	Stanford's CMT system	Colloid Micro Thruster	Sodium-Iodide/glycerol	Micro-satellite propulsion	Station keeping/Orbit Maintenance	4.00E-06	200

Table 2 - Summary of Propulsion Systems *Part B*

Spacecraft	**Mass** [kg]		**Delta-v** [m/s]	**O/F**	**Density** [kg/m^3]		**Density Propellant** [kg/m^3]	**Total Impulse** [Ns]
	Burnout	**Total**			***Oxidizer***	***Fuel***		
MESSENGER (2004)	507.90	1,107.00	2,422.90	0.85	1,428.58	1,008	1,201.24	1,863,063.21
Chang' E-2 (2010)	1,180.00	2,480.00	2,273.33	1.65	1,428.58	880	1,221.57	3,978,936.00
TDRS-L (2014)	1,418.00	3,454.00	2,724.91	1.65	1,443	880	1,230.55	6,231,625.92
Astra 1KR (2006)	2,760.00	4,332.00	1,432.84	0.85	1,428.58	1,008	1,201.24	4,996,507.68
AEHF *LAE* (2010)	4,050.00	6,170.00	1,404.14	1.34	1,443	1,008	1,257.10	7,071,048.00
Galaxy 17 *LAE* (2007)	2,659.00	4,100.00	1,350.89	1.65	1,008	880	959.93	4,495,314.78
Bi-propellant H_2O_2/Isooctane	13,420.67	19,349.71	954.75	6.50	1,431	692	1,332.47	15,471,590.86
Julius Verne ATV-001 *200N Bi-prop. Thruster* (2008)	13,498.00	19,356.00	954.75	1.65	1,433	871	1,220.92	15,516,084.60
OSIRIS-Rex *200N Bi-prop. Thruster* (2016)	17,050.00	17,950.00	144.83	1.65	1,443	880	1,230.55	2,533,923.00
LRO (2009)	1,018.00	1,916.00	1,271.79	1.00	1,008	-	1,008	1,805,922.90
AEHF *23N Thruster* (2010)	5,540.00	6,170.00	237.73	1.00	1,008	-	1,008	1,390,567.50
Galaxy 17 *Thruster* (2007)	3,218.00	4,100.00	691.49	1.65	1,008	880	959.93	2,517,854.22
OSIRIS-Rex *Hall Thruster* (2016)	5,950.00	17,950.00	32,496.57	1.00	-	2,949	2,949	353,160,000.00
SMART-1 *1N Thruster* (2003)	367.00	370.00	17.57	1.00	1,008	-	1,008	6,474.60
Astrium *1N Thruster*	0.29	52.00	11,199.15	1.00	1,008	-	1,008	111,600.52
PRISMA (2010)	0.35	5.85	6,492.47	1.00	1,240	-	1,240	12,679.43
AEHF *1N Thruster* (2010)	5,540.00	6,170.00	237.73	1.00	1,008	-	1,008	1,390,567.50

Future Systems	-		-	1.00	-	2,949	2,949	-
AEHF *Hall Thruster* (2010)	5,770.00	6,170.00	1,315.07	1.00	-	2,949	2,949	7,848,000.00
Boeing 702HP	150.00	416.00	35,023.42	1.00	-	2,949	2,949	9,133,110.00
SMART-1 *Plasma Thruster* (2003)	285.00	367.00	3,820.25	1.00	-	2,949	2,949	1,238,806.80
ESA: Porba-2 (2009)	118.00	130.00	45.61	1.00	-	2,949	2,949	5,650.56
CMT (2003)	20.00	20.50	48.45	-	-	-	-	981.00

The previous tables display that *liquid apogee engines* (LAE) have thrust capacities between 400 N - 500 N for most GEO satellites. Thrusts levels for smaller satellites are usually equal to or below 1 N for each thruster. Smaller lunar spacecraft can have orbit insertion thrusters around 50 N-100 N depending on the size of the spacecraft. Altitude control systems (ACS) are used for station keeping, orbit maintenance, and several other adjustment maneuvers. Thrust levels for such an operation depend on the size of the vehicle ranging from 1 mN to 1 N for smaller satellites and 1 N to 23 N for larger satellites. For large vehicles greater than 7,000 kg, 200 N class thrusters have been used for ACS and braking. Few cases can be found where 200 N thrusters have been used, however the 2008 Jules Verne ATV-001 presents such a case.

Vehicle Comparison: *Jules Verne ATV-001*

The Jules Verne is a transfer vehicle developed by the ESA for a supply mission in 2008. The propulsion system used 28 of Astrium's 220 N bipropellant engines to provide altitude control and braking maneuverers for the nearly 20 ton transfer vehicle. The engine produced a nominal thrust of 216 N with a vacuum specific impulse of 270 s [9].The engine used a MON/MMH propellant system which was stored by 8 titanium tanks. The specifications of the Jules Verne ATV-001 can be seen in Table 3.

Table 3 - Jules Verne ATV-001 Propulsion System Comparison: ***200 N Thruster***

Jules Verne ATV-001	***Astrium's 200N Bipropellant Thruster***		***200N Bipropellant HTP/Isooctane***	
Delta-v [m/s^2]	954.7528		A	B
Wet Mass [kg]	19356.00		19,366.76	19,349.70
Dry Mass [kg]	13498.00		13,420.67	
Propellant Mass [kg]	5858.00		5,949.09	5929.03
Propellants	MON-3/MMH		HTP/Isooctane	
Thruster	Astrium 200 N Bi-propellant Thruster		HTP 200 N Bi-propellant Thruster	
Number of Ox Tanks	4		4	
Number of Fuel Tanks	4		4	
Shape of Tanks	Circular		Circular	
Ivac [s]	270		266.00	
Thrust [N]	216.00		250.00	
O/F	1.65		6.50	
	Oxidizer	***Fuel***	***Oxidizer***	***Fuel***
Density [kg/m^3]	1,433.00	871.00	1,431.00	692.00
Density of Propellant [kg/m^3]	1220.92		1332.47	
Mass of Propellant [kg]	3,647.43	2,210.57	5,153.28	792.81
Volume of Propellant per Tank [m^3]	0.636	0.634	0.900	0.286
Percentage of Tank filled	75.11%	74.89%	75.11%	74.89%
Tank Alloy	Ti-15-3		Ti-15-3	
Mass of Tank [kg]	64.00		80.61	37.72
Inner Diameter of Tank [m]	1.1740		1.3180	0.9006
Density of Alloy [kg/m^3]	4,780		4,780	
Tank Inner Volume [m^3]	0.8472		1.1987	0.3825
Tank Alloy Volume [m^3]	0.0134		0.0169	0.0079
Tank Total Volume [m^3]	0.8607		1.2156	0.3903
Tank Total Radius [m]	0.5901		0.6621	0.4534
Tank Alloy Radius [m]	0.0031		0.0031	
Price of Propellant [$/kg]	$ 348.13	$ 329.76	$ 4.14	$ 3.48
Price of Alloy [$/kg]	$ 0.95		$ 0.95	
Total Price of Propellant [$]	$ 1,269,781.19	$ 728,956.26	$ 21,334.57	$ 2,758.99
Total Price of Alloy [$]	$ 486.40		$ 449.67	
Total Price of Fuel and Tank Raw Material [$]	$ 1,999,223.84		$ 24,543.23	

Radtke, W. "Manufacturing of Advanced Titanium (Lined) Propellant Tanks and High Pressure Vessels." 4th International Spacecraft Propulsion Conference. Vol. 555. 2004.

Burgon, Ross, et al. "Maneuver planning optimization for spacecraft formation flying missions." *The Journal of the Astronautical Sciences* 56.4 (2008): 545-571.

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March 2014

The comparison was made by replacing the 2008 Jules Verne ATV-001's MON/MMH propellant system with the HTP/Isooctane propellant system being develop at IOA. By using the total impulse of the MON/MMH system, the amount of HTP/Isooctane propellant needed to propel the spacecraft for the same duration can be calculated.

$$I_{tot} = I_{sp} m_{prop} \tag{1-1}$$

$$I_{totA} = I_{totB} \tag{1-2}$$

$$I_{spA} m_{propA} = I_{spB} m_{propB} \tag{1-3}$$

$$m_{propB} = \frac{(I_{spA} m_{propA})}{I_{spB}} \tag{1-4}$$

The amount of propellant needed to propel the dry mass of the 2008 Jules Verne is roughly 5496 kg. This is however assuming that the tanks which stored the MON/MMH propellant remain the same size for the HTP/Isooctane propellant. In reality, the advantage of using the HTP/Isooctane propellant is its high density, meaning that it requires smaller tanks to store the same liquid mass of the MON/MMH system. Therefore the size of the tanks required to store 5496 kg of HTP/Isooctane is 41% larger and 54% smaller for the oxidizer and fuel tanks respectively. This is assuming a similar fill ratio to the MON/MMH system. This leads to a reduction of 9.66 kg per tank and overall dry mass reduction of 77.33 kg. Taking this into account, the actual amount of propellant needed to propel the spacecraft with the reduced weight can be calculated with the rocket equation:

$$m_{prop} = m_{dry}\left(e^{\frac{\Delta v}{I_{sp} g}} - 1\right) \tag{1-5}$$

With the altered propellant tanks, the amount of propellant needed to obtain the same *delta-v* as the 2008 Jules Verne ATV-001 is 5929 kg. This leads to an overall reduction of wet mass by only 0.03%.

The price reduction however is much more significant. Through obtaining prices from the Defense Logistics Agency, propellant prices, as well as the tank materials prices, can be calculated for the Jules ATV-001 in today's market prices. In the current market the Jules Verne ATV-001 propellant and raw tank material would cost $1,999,223.84 compared to the cost of using the HTP/Isooctane altered scenario of $24,543.23. This does not include handling and transportation costs that arise from using highly toxic propellants. Table 4 shows the compiled prices of several popular propellants in terms of their bulk cost per kilogram.

Table 4 - Market Prices of Bulk Spacecraft Propellants and Materials

NSN	Product Name	Price per kg
9135-00-926-2165	N2O4-MON-1 Bulk	$ 348.13
9135-01-056-5010	N2O4-MON-10 Bulk	$ 348.13
9135-01-013-8569	N2O4-MON-3 Bulk	$ 348.13
9135-00-754-2694	N2O4-NTO Bulk	$ 348.13
9135-00-753-4919	A-50(Hydrazine)	$ 329.77
9135-00-753-4568	AH (Hydrazine)	$ 329.77
9135-01-373-6641	High Purity Hydrazine	$ 329.77
9135-00-148-9813	MMH (Hydrazine) Bulk	$ 329.77
9135-00-687-4293	UDMH (Hydrazine)	$ 329.77
9135-00-754-4613	Nitric Acid, Red Fuming	$ 134.61
9135-01-239-8066	Liquid Methane	$ 9.89
6830-01-468-6756	Xenon, 99.999% Grade E	$ 8.73
9135-00-611-1347	Liquid Hydrogen	$ 8.31
9135-01-048-5285	JP-10	$ 6.40
9130-01-539-9895	Kerosene, RP-2, Bulk	$ 5.05
9135-01-474-0372	Hydrogen Peroxide (98%)	$ 4.14
6810-00-097-4161	Isooctane, Reference Fuel	$ 3.48
9130-00-543-7429	Kerosene, RP-1 (Bulk)	$ 2.28
9535-01-445-3442	Plate, Metal (Ti-15V-3Cr-3Sn-3Al)	$ 0.95
9135-01-526-5184	Methanol	$ 0.94
6830-00-285-4769	Liquid Nitrogen	$ 0.42
6830-01-527-7267	Liquid Oxygen	$ 0.18
Prices were obtained from: United States. Defense Logistics Agency. Logistics Information Services. Web. 27 Mar. 2014. <http://www.dlis.dla.mil/webflis/pub/pub_search.aspx>.		

Green Propellant Standards

When developing green propellants to replace the toxic standard propellants, specific characteristics should be taken into consideration; mainly the toxicity, performance, storability, and manufacturing costs. Most proposed replacements are newly developed with high performance results. However, chemicals that initially come out of R&D tend to carry high manufacturing costs. In most cases manufacturing plants are setup over the course of several years due to the cost and time of developing new manufacturing technology. Leaning out the manufacturing process occurs only after production has begun; meaning there will be high cost inefficiencies that will be encountered. Therefore raw materials cannot be the only consideration when developing a cost analysis for new propellants. With this said, there are a number of studies that have shown that there are several chemicals that can outperform the accepted standard propellants both in bipropellant and monopropellant systems. To date the only outperforming green monopropellant which has been flight proven is the LMP-103S monopropellant used on PRISMA's propulsion system.

Monopropellants - HAN, ADN, HNF

Potential green liquid monopropellants include Hydroxyl Ammonium Nitrate (HAN), Ammonium Dinitrate (ADN), Hydrazinium Nitroformate (HNF) [11]. Ammonium nitrate and hydrazinium nitrate have also been considered for hydrazine replacements. HAN/HN based monopropellants have a density of 1.4 - 1.5 g/cm^3 with a toxicity level 1/10,000 that of hydrazine. HAN-based monopropellant, SHP163, has a similar density to HTP at 1.42 g/cm^3 and a specific impulse of about 254 s. The Air Force has also recently developed the green monopropellant AF-M315E. The new propellant has a 12% higher I_{sp} than hydrazine and is 45% more dense. The unique feature of AF-M315E is that it is unable to freeze due to a glass transition.

Table 5 - Green Monopropellant Performances

Propellant	Density [g/cm^3]	Theoretical I_{sp} [s]	Density I_{sp} [s*g/cm^3]
AF-M315E	1.47	257	377
LP1846 (HAN)	1.4	262	376
SHP163 (HAN)	1.442	254	366
HNF-based	1.4	260	354
LMP-103S (ADN)	1.24	253	313
HAN/HN-based	1.4	210	294
Hydrogen peroxide (98%)	1.431	182	260
LTHG	1.3	191	254
Hydrazine	1.01	239	241

Bipropellants- Ionic Liquids & Organometallics

For bipropellant systems, ionic liquids and organometallics have recently caught the attention of several research facilities. The particular characteristics that deem such chemicals desirable are their high specific gravity, high hydrogen content, and light molecular structure. There low freezing point also makes them desirable candidates for storable propellants. For these reasons hydrides have been researched as additives for hydrogen storage at Politecnico di Milano. The main propose of using hydrides is their ability to store high volumes of hydrogen at ambient conditions which can be released during combustion [4]. Problems have been encountered with ionic liquids in the past due to their viscosity and ignition delay. These are two vital components since the viscosity determines the miscibility of the propellants, while a long ignition delay can develop into an explosive.

Ionic Liquids

In a study done in 2000 at GIT, a doped ethanol nontoxic hypergolic miscible fuel (NHMF) was combined with high test peroxide (HTP) for a hypergolic bipropellant. Scientists at GIT considered the performance of NHMF/HTP against the standard monomethylhydrazine (MMH) / nitrogen tetroxide (NTO) propellant [10].The propellants' performance approached that of the NTO/MMH yet it was determined that the propellant formulations have a reasonable level of technical risk, mostly residing in the development of soluble fuel catalysts that are required for hypergolic ignition with HTP [10]. Research has suggested that the determining characteristic for hypergolic ionic liquids is the heat of formation which has been calculated to be directly related the number of nitrogen-nitrogen bonds in the ionic species. In light of this information researchers decided to synthesize the cation 2,2-dimethyltriazanium (DZMA). The cation has been one of the first to hypergolicly react without a dependency on a particular anion. In pair with the nitrate anion, 2,2-dimethyltriazanium nitrate (DMTN) , the ionic liquid was able reach specific impulses of 228 s with a density of 1.47 g/cm^3 and ID of 4ms [27].

While ionic liquids have the potential to be cost effective, the toxicity is still a concern since several ionic liquids are hydrazine derivatives. An in vitro study done by the USAF to determine the toxicity of newly developed high energy chemicals (HEC) exposes thirteen chemicals to the hepatocytes in rats [12].The effects of short-term exposure (4 hours) of hepatocytes to HECs were investigated with reference to viability, mitochondrial function, reactive oxygen species generation, reduced and oxidized glutathione. The HECs are comprised primarily of hydrazine derivatives, amino containing compounds, and triazole containing compounds. The DMTN chemical was labeled as a low toxicity chemical. Results showed that triazole containing compounds did not show significant toxicity readings even at high doses. Hydrazine containing compounds, including HEHN, reduced mitochondrial function in a concentration dependent manner, marking them high toxicity chemicals.

Table 6 - Toxicity of High Energy Chemicals (HEC)

HEC	Toxicity
Hydrazine derivatives	
hydrazinium nitrate, HZN	High Toxicity
2-hydroxyethylhydrazine nitrate, HEHN	High Toxicity
1,2-diettiylhydrazine nitrate, DEHN	High Toxicity
1,4-dihydrazine nitrate, DHTN	High Toxicity
methylhydrazine nitrate, MHN	High Toxicity
diaminoguanidine nitrate, DAGN	High Toxicity
nitroaminoguanidine nitrate, NAGN	High Toxicity
Amino containing compounds	
ethanolamine nitrate, EAN	Medium Toxicity
histamine dinitrate, HDN	Medium Toxicity
methoxylamine nitrate, MAN	Medium Toxicity
Triazole containing compounds	
1,2,4-triazole nitrate TN	Low toxicity
4-amino-1,2,4-triazole nitrate, ATN	Low toxicity
Ammonium Salt	
2,2-dimethyltriazanium nitrate, DMTN	Low toxicity

Organometallics

The lab at Swift Enterprises conducted performance studies on organometallic doped kerosene which was mixed hypergolicly with HTP. The team compares 7 different organometallic fuels including the well-known "Block O" developed by the USAF. Doping the kerosene has the same effect as it would on hydrogen storage, creating a denser, storable fuel. The compound Li_3AlH_6 releases large amounts of hydrogen when combusted with decomposed HTP. Performance studies done by the scientists demonstrate that lithium borohydride ($LiBH_4$), lithium aluminum hydride ($LiAlH_4$) and lithium hexahydridoaluminate (Li_3AlH_6) have higher performance than NTO/MMH. Of particular interest is Li_3AlH_6 used in combination with anhydrous hydrogen peroxide. This propellant combination has performance characteristics 30% greater than NTO/MMH while maintaining virtually the same combustion chamber temperature [17].

Table 7 - Green Bipropellant Comparison

Oxidizer	**Fuel**	**Density [kg/m³]**		**O/F**	**Propellant Density [kg/m³]**	**Isp vacc [s]**	**Density I_{sp} [s*g/cm³]**	**Mass of Propellant [kg]**
		Oxidizer	**Fuel**					
HTP 98%	Lithium Aluminum Hexahydride	1,431.00	994.00	0.70	1,173.94	469.00	588	580.09
CIF5	Hydrazine	1,645.00	1,008.00	2.70	1,472.84	381.00	561	714.07
HTP 98%	Quadricyclane	1,431.00	1,000.00	6.60	1,374.29	360.00	511	755.73
HTP 98%	Quadrasilane	1,431.00	900.00	5.60	1,350.55	366.00	510	743.34
HTP 98%	Lithium Aluminum Hydride	1,431.00	900.00	0.90	1,151.53	407.00	484	668.45
HTP 98%	RP-1	1,431.00	801.00	7.30	1,355.10	348.92	472	779.72
HTP 98%	**Isooctane**	**1,431.00**	**691.00**	**7.40**	**1,342.90**	**349.43**	**469**	**778.59**
HTP 98%	Lithium Borohydride	1,431.00	700.00	1.60	1,149.85	395.00	461	688.76
HTP 98%	n-Butyllithium	1,431.00	800.00	6.80	1,350.10	355.00	460	766.37
NTO	MMH	1,443.00	900.00	2.50	1,287.86	364.00	458	747.42
HTP 98%	Block O	1,431.00	1,000.00	2.30	1,300.39	341.00	448	797.83
HTP 98%	Lithium Hydride	1,431.00	820.00	1.10	1,140.05	348.00	431	781.78
HTP 98%	Lithium Amide	1,431.00	1,200.00	2.20	1,358.81	317.00	427	858.24
HTP 98%	Lithium Methoxide	1,431.00	900.00	2.70	1,287.49	314.00	380	866.44

The downfall of this comparison is that the data was calculated using a 10,000 lbf, 500 psi, and 250 expansion ratio. Engines of this magnitude would more likely be propelled by the high performance LOX/LH_2 booster engines that require large quantities of fuel. The high performance benefit of organometallics would be trumped by the high cost of manufacturing. LOX/LH_2 remains one of the cheapest propellant combinations on economic market.

Satellite Applications

Satellites can be categorized as; communication, military, navigation, scientific, or weather orientated. The type of satellite will in most cases determine the payload. An analysis of current propulsion systems on various satellites can determine the proper application of a green HTP/Isooctane thruster. Satellite data including: *Name, Orbit, Perigee/Apogee, Bus Model, Wet Mass, Dry Mass, Main Propulsion Engine, and Thrust* were considered in determining the correct mass to thrust relationship. Provided by the *Union of Concerned Scientist* satellite database, data from more than 1100 satellites were taken into account when developing the trends in *Altitude vs. Mass*. The average of the perigee and apogee were taken to represent the altitude. The mass is based of off the total wet mass of the satellite at the time of its launch. The different orbits considered are *GEO, MEO,* and *LEO*.

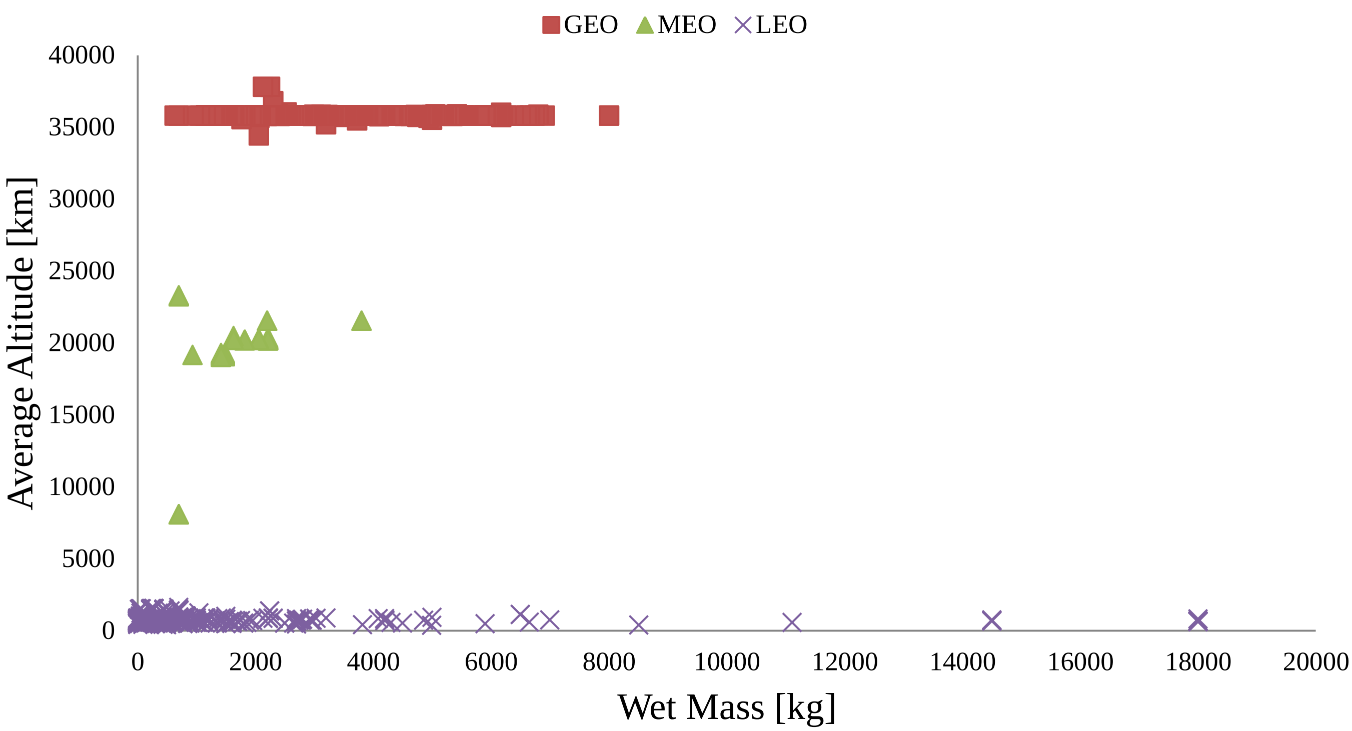

Figure 1 - *Trends in Satellites' Dependency on Mass in Relation to Altitude*

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March 2014

Figure 1 displays that the altitude of low earth orbit and geostationary satellites are independent of their masses. However, MEO satellites have a positive linear dependency. The average mass of the orbital satellite are: GEO - *3,711 kg*, MEO – *1,689 kg*, & LEO - *932 kg*.

To determine the proper thrust application for the HTP/Isooctane system, a sample of propulsion systems were selected from the satellites from the UCS database. Table 8- Sample Satellite Comparison of Altitude, Wet Mass, & Main Engine Thrust displays the main propulsion systems of the selected satellites. The relationship between thrust and wet mass is demonstrated in Figure 2 - *Wet Mass Influence on Satellites' Main Engine Thrust*

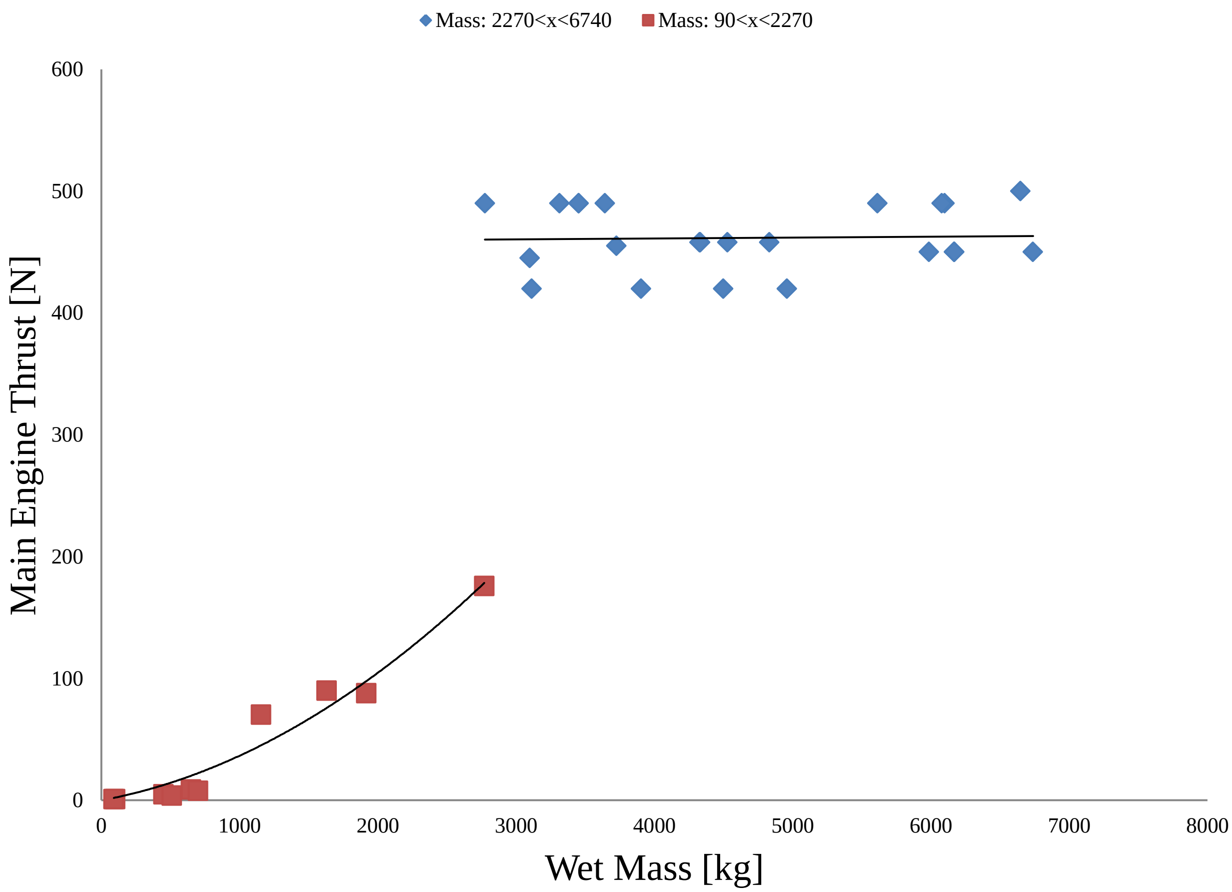

Figure 2 - *Wet Mass Influence on Satellites' Main Engine Thrust*

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Table 8- Sample Satellite Comparison of Altitude, Wet Mass, & Main Engine Thrust

Satellite	Orbit	Perigee [km]	Apogee [km]	Bus Model	Mass [kg]		Main Engine	Thrust [N]	
					Wet	Dry		Per Engine	Total
Inmarsat-4A F4	GEO	35,771	35,801	Alphabus	6649	2449	500N EAM	500	500
Echostar 17	GEO	35,781	35,794	LS-1300E	6100	3225	R-4D-10	490	490
Sirius FM6	GEO	35,784	35,791	LS-1300	6080	2940	R-4D, 4xSPT-100	490	490
Intelsat 14	GEO	35,771	35,800	LS-1300	5614	2517	R-4D-11	490	490
Astra 2C	GEO	35,768	35,804	BSS-601HP	3643	2000	R-4D-11-300	490	490
TDRS-K	GEO	35,782	35,794	BSS-601HP	3454	2000	R-4D-11-300	490	490
TDRS-L	GEO	35,780	35,785	BSS-601HP	3454	1418	R-4D-11-300	490	490
Astra 2B	GEO	35,772	35,801	Eurostar-2000+	3315	1400	R-4D	490	490
Asiastar	GEO	35,773	35,801	Eurostar-2000+	2775	1530	R-4D	490	490
SBIRS-GEO 1	GEO	35,778	35,795	A2100M	4833	-	LEROS-1C	458	458
SBIRS-GEO 2	GEO	35,770	35,790	A2100M	4530	-	LEROS-1C	458	458
Astra 1KR	GEO	35,785	35,800	A2100AX	4332	2760	LEROS-1C	458	458
Echostar 12	GEO	35,782	35,791	A2100AXS	4328	2760	LEROS-1C	458	458
SD-RADIO 1	EEO	23,783	47,100	LS-1300	3727	1570	455N LAE	455	455
MUOS 2	EEO	3,802	35,787	A2100M	6740	3812	IHI BT-4	450	450
AEHF-2	GEO	35,700	35,700	A2100M	6170	3810	IHI BT-4	450	450
AEHF-1	GEO	35,872	36,103	A2100M	6169	3810	IHI BT-4	450	450
AEHF 3	GEO	35,700	35,700	A2100M	6169	3810	IHI BT-4	450	450
WGS F2	GEO	35,771	35,802	BSS-702	5987	3253	LAE 450 N	450	450
SDO	GEO	35,785	35,798	-	3100	1700	R-4D-15DM	445	445
AMC-12	GEO	35,772	35,799	Spacebus 4000 C3	4959	2286	S400	420	420
Chinasat 9	GEO	35,761	35,811	Spacebus 4000 C2	4500	1839	S400-12	420	420
Hot Bird 6	GEO	315	45,863	Spacebus-3000B3	3905	1900	S400-12	420	420
Hispasat 1C	GEO	35,764	35,808	Spacebus-3000B2	3112	1304	S400-12	420	420
LDCM	LEO	683	692	SA-200HP	2770	1512	8 x 22 N thrusters	22	176
GPS IIF-5	MEO	20,495	20,495	AS-4000	1630	1485	4x22.2N Hydrazine	22.5	90
LRO/LCRoss	HTO	30	216	-	1916	1018	88N Thruster	88	88
DSCS-3 B8 (USA 148)	GEO	35,706	35,868	DSCS-3B8	1156.6	884.5	16 x 4.4N thrusters	4.4	70.4
RBSP-A	EEO	591	30,534	-	648	-	8 × MR-103G	1.12	8.96
Galileo IOV-1 PFM	MEO	23,240	23,306	-	700	625	8x1N Hydrazine	1	8
Globalstar M063	LEO	914	930	LS-400	450	400	5 x 1N thruster CHT-1	1	5
Jason - 1	MEO	1,328	1,340	Proteus	511	-	4 x 1N thruster CHT-1	1	4
ExactView 1	LEO	806	821	SSTL-100	100	83	Liquefied Butane gas	0.1	1
NigeriaSat 1	LEO	675	694	SSTL-100	90.1	83	Liquefied Butane gas	0.1	1

For satellites with a mass less than 2,270 kg, an exponential dependency can be observed for thrust in Figure 2 - *Wet Mass Influence on Satellites' Main Engine Thrust*. Thrust will transfer to a linear, nondependent trend as wet mass crosses this threshold. Causes of such trends may be due to gravitational forces in low and medium earth orbits. Larger masses would require a greater thrust for major maneuvers. Based on the gravitational attraction equation (1-6), Figure 3 demonstrates the gravitational forces experienced by satellites in Table 8.

$$F = \frac{GM_{Earth}m_{sat}}{(R_{Earth}r_{altitude})^2} \quad (1\text{-}6)$$

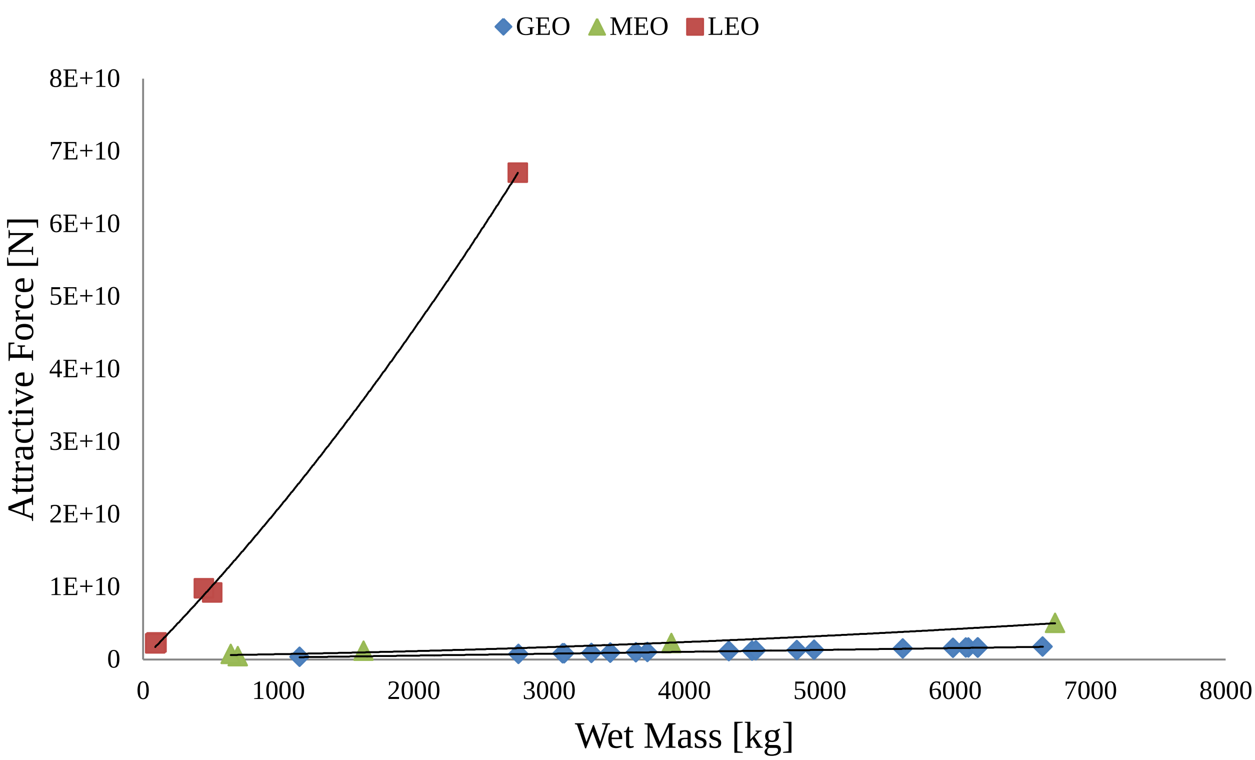

Figure 3 - *Display of Gravitational Forces for GEO, MEO, & LEO Satellites' Wet Mass*

Figure 2 and 3 display a clear trend in mass dependency in LEO satellites which is most likely caused by gravitational forces. These forces will influence the thrust levels of LEO satellites' propulsion systems. The comparison of the ATV-001 in Table 3 shows that the cost of propellants should also influence the type of thruster installed in a propulsion system. Due to its low cost of production, HTP/Isooctane would be best utilized in applications of large propellant expulsion. This correlates with high thrust and short duration applications. In 2003, the Air Force Research Lab Edwards reported the average *delta-v* for several satellite maneuvers [11]. A specific application for high thrust HTP/Isooctane propulsion system can be determined in terms of its *delta-v*.

Table 9 - Average Delta-v for Satellite Operations

Maneuver	***Delta-v* [m/s]**	
	Minimum	Maximum
Orbital Change in LEO (400 km - 1000 km)	300	
Station Keeping in GEO/year	50	100
Orbital Change LEO to GEO (400 km - 36000 km)	3,950	4,260
De-orbit LEO to Earth	500	2,000
Transfer GTO to GEO	1,500	1,800
LEO to Translunar Orbit	3,100	
GTO to Lunar Orbit	1,250	1,400

Based off Table 9 it is evident that a GTO-GEO transfer thruster would be an appropriate application for a high thrust HTP/Isooctane propulsion system. A LEO application is undesirable due to the thrust restrictions that were displayed in Figure 2. Station keeping applications for GEO satellites is also undesirable due to the need for long term, low thrust (1N-23N), and high specific impulse. EP devices are most ideal for these sorts of operations. A LEO to GEO transfer could be taken into consideration although solid and hybrid propellant systems can outperform, deliver higher thrusts, and also be dumped to reduce weight after a long term, high thrust application. The same argument can be applied to a LEO to translunar orbit as well. A GTO to lunar orbit can be an applicable operation for a HTP/Isooctane high thrust system, such as the system used on the Chang’e-2 lunar orbiter. Such vehicles are rare compared to the amount of GEO satellites that are in operation today. Therefore it is more beneficial to focus on GEO satellites, in particular a GTO to GEO operation.

Satellite Determination for a 500 N HTP/Isooctane Thruster

Researchers at IOA have developed a preliminary design for a 500 N HTP/Isooctane thruster with specific impulse of 311 s. Based on this design, the satellite that would best utilize this propulsion system can be determined. Propulsion systems with an orbit injection/insertion operation in Table 1 display thrust levels from 400N-500 N. For a delta-v of 1500 m/s, the average propellant to dry vehicle mass ratio for the GEO satellites with corresponding thrust levels in Table 8 is 62%. The ratio between propellant needed for a 1500 m/s velocity change and the total propellant reported for GEO satellites in Table 8 is 69%. As mentioned before the average GEO satellite has a wet mass of 3,711 kg. Taking these figures into account the following figures can be calculated; the mass of HTP/Isooctane needed to propel a 3,711 kg wet satellite for a delta-v of 1500 m/s, the total mass that would, on average, be stored on the GEO satellite at launch; and the dry mass of the satellite for such a situation.

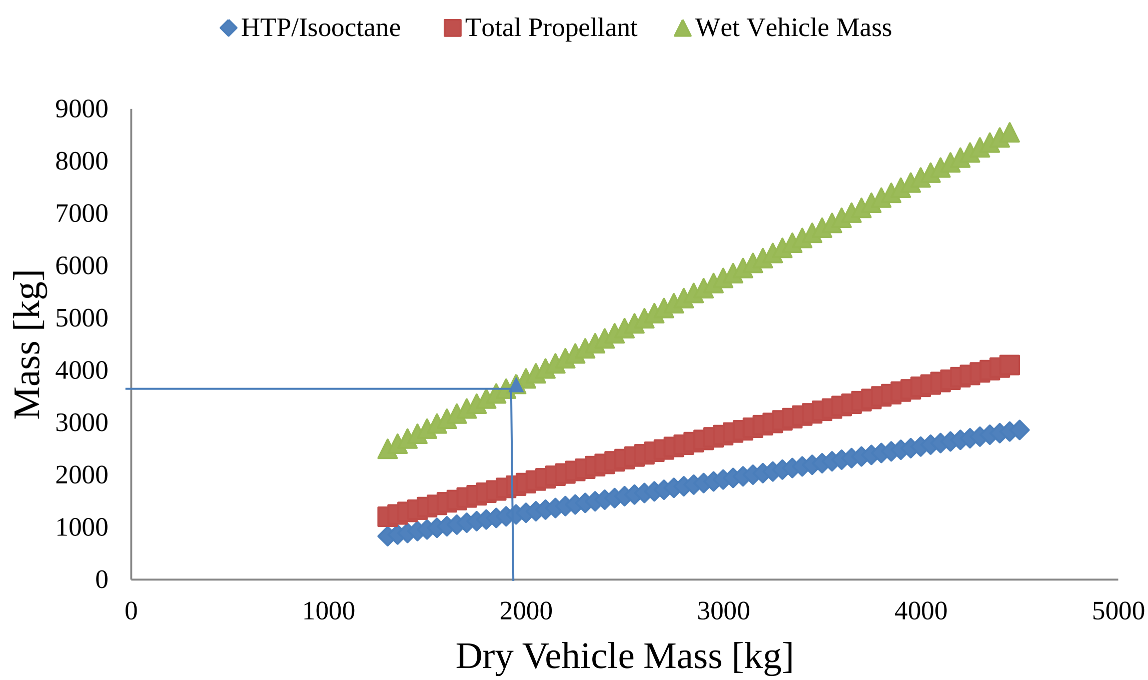

Figure 4 - ***Mass Budget for Satellite with HTP/Isooctane 500 N Thruster***

Table 10 - Satellite Specifications for a HTP/Isooctane 500 N Propulsion System

Propulsion System		
Propulsion System	IOA Green Bipropellant Thruster	
Function	Orbit Injection GTO-GEO	
Propellants	HTP/Isooctane	
Thrust [N]	500	
O/F	7.1	
Isp [s]	311	
Delta-v [m/s]	1500	
Propellant Density [kg/m^3]	1339	
Satellite System		
Satellite System	**Determined Satellite**	**Hot Bird 6**
Dry Mass [kg]	1933	1900
HTP/Isooctane Mass [kg]	1227	-
Total Propellant Mass [kg]	1778	2005
Wet Vehicle Mass [kg]	3711	3905
Cost of HTP	$ 4,452.65	-
Cost of Isooctane	$ 527.16	-
Total Propellant Cost	$ 4,979.80	-

Table 1 summarizes the optimum satellite that could accompany a 500 N HTP/ Isooctane thruster. The determined satellite resembles the GEO satellite the Hot Bird 6 with a Spacebus-3000B3 Platform.

Conclusion

Analysis of the different propulsion systems that exist in today's space vehicles display the increasing demand for alternate nontoxic propellants. The cost of toxic propellants is exponentially higher than all other propellants on the market today. Research in the development of green propellants is favoring ionic liquids for bipropellant systems as well as ADN, HAN, and HNF based propellants for monopropellants. High test peroxide and isooctane offer a highly affordable and less toxic solution to the MON/MMH standard. The slight decrease in performance can be traded off in its propellant density and low cost production in high thrust applications. The most likely application is in a GTO to GEO orbit injection thruster that operates between 400 N - 500 N. Future research should focus on the additives that can enhance the performance of the HTP/Isooctane propellant systems. As new fuels are being developed a strong consideration should be taken for a HTP oxidizer.

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