Cost Effective Propulsion Systems for Small Satellites
Corners to Cut, Corners to Honor

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Abstract: This paper will examine the development and test philosophy of a new, miniature pulsed plasma thruster destined for flight on the UW Dawgstar nanosatellite, and the development and test philosophy of small hydroxyl ammonium nitrate (HAN) thrusters intended for satellite use. The key to cost effective development is to know when both a rigorous analysis and a full test program is needed, and when the use of heritage hardware in a similar application may permit more latitude. The discussion will include a review of system challenges and considerations. Techniques used to design, build, and test new propulsion systems will be compared with techniques used to adapt mature hydrazine technology to new applications. As a specific example, long-term, full temperature range, materials compatibility testing for "green" monopropellants such as HAN is critical to developing suitable tanks, lines and components. In contrast, system level thermal analysis (without testing) will usually be adequate because HAN propulsion systems will be designed to take advantage of heritage hydrazine systems "lessons

Introduction

Engineers at PRIMEX Aerospace Company (formerly Rocket Research Company and Olin Aerospace Company) have over twenty-five years experience[1] designing, building and testing monopropellant hydrazine systems. Much of what we have learned is directly applicable to new propellant systems, whether they be monopropellant hydrazine systems, "green" monopropellant blend systems such as HAN/glycine, or the rather different approach offered by a group of pulsed plasma thrusters and their associated electronics. In any case, all but the smallest and simplest of satellites requires some sort of propulsion system in order to position it where its owners want it to be and move or adjust it as required. Since the days of large budgets and an unlimited supply of engineering talent are largely over, we are faced with designing these propulsion systems on a budget. Cost constraints mean that it is extremely critical to determine up front which parameters require careful evaluation for an individual mission and which may be evaluated via similarity and largely dismissed.

This paper will examine some case histories from the EO-1 program (both a monopropellant hydrazine system and an experimental pulsed plasma thruster scheduled for launch in the fall of 2000). We will also examine a HAN propulsion system for the Virginia Tech Hokie Sat program which was tentatively planned[2], but unable to fly due to the lack of an available tank, and miniature pulsed plasma thrusters for the University of Washington Dawgstar satellite.

Critical parameters which must be addressed via analysis, test, both analysis and test, or similarity include:

- Design philosophy—what is this propulsion system intended to do and how can we best package it to function as intended?
- Structural integrity, in particular of the propellant tanks
- Thermal management-keeping the propellant above freezing and below autoignition and the soft seals (e.g. propellant valve seats) below their rated temperatures
- Plume management, in particular plume impingement and its effect on adjacent surfaces and ACS management
- Reliability—needs to focus on the mission requirements (e.g. a propulsion system that fires for 20 minutes at the beginning of the mission and is never again used has very different requirements than one that must operate regularly over the course of 15 to 20 years). The goal should be the highest reliability consistent with the mission requirements.
- Quality—as with reliability, quality must be defined with reference to mission needs. What is a “quality” system for one mission may be woefully inadequate for another.
- Safety—Includes launch, protection of personnel, and safety of both the satellite and the launch vehicle
- Cost—best value for the budget available
- Customer management—how many official document submittals are required and what can best be managed in an integrated product development (IPD) environment

This paper is all about choices. Some testing is required, some analysis is inevitable, and some requirements may be satisfied by a relatively casual look at the propulsion system design. The key is to making the most technically correct, cost-effective choices when required (usually at the earliest possible moment). Experience provides many lessons on what is cost effective and what is not. As an industry, we must get away from the mentality of “doing it the way it was done before” because this can carry non-cost effective practices forward with the good ones. The trick is to learn from past mistakes and carry those lessons forward into each subsequent project.

Nomenclature

ACS	Attitude Control System
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
APL	Applied Physics Laboratory at Johns Hopkins University
CMOS	Complementary Metal Oxide Silicone
DARPA	Defense Advanced Research Project Agency
EO-1	Earth Observing-1 Satellite
DSMC	Direct Simulation Monte Carlo Analysis
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
GSFC	NASA Goddard Space Flight Center
HAN	Hydroxyl Ammonium Nitrate
HAPS	Hydrazine Auxiliary Propulsion System for the Pegasus Launch Vehicle

HPB	Hydrazine Propellant Blends
IPD	Integrated Product Development
ION-F	Ionospheric Observation Nanosat Formation
JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
PPT	Pulsed Plasma Thruster
PPU	Power Processing Unit
PSI	Pressure Systems, Inc.
STEP	Space Test Experiment Platform
USU	Utah State University
UW	University of Washington

Small Monopropellant Hydrazine Systems

Cost-effective propulsion system design generally begins with a qualified propellant tank. Range safety requires that newly designed propellant tanks have complete fracture mechanics analysis and full qualification testing including vibration, proof pressure cycle testing, and burst testing. As part of the burst testing, it is necessary to verify a "leak before burst" design that does not produce shrapnel when it fails. And these are reasonable requirements—a burst tank compromises not just the entire spacecraft mission but also the launch vehicle and more importantly the personnel working around it.

But for the end user designing a single satellite, the cost of a second tank and associated qualification testing is often prohibitive. Fortunately, there are many qualified tanks available from a variety of suppliers. The propulsion system designer is generally left with the tasks of choosing an appropriate tank in the right size (or slightly larger), designing the mounting interface to transmit loads no greater than previously tested, and analyzing any areas of apparent non-compliance.

For instance, on the EO-1 program, the PSI P/N 80389-101 tank was chosen. The heritage of this tank is the STEP IV program. It is a 15" diameter skirt mounted spherical tank with a diaphragm for positive propellant expulsion. The tank was mounted to the customer furnished spacecraft deck. The thrusters and other components were plumbed to the tank and spacecraft deck, and the deck was returned to Swales for integration into the spacecraft. Figure 1 shows the completed propulsion system.

Figure 1—EO-1 Propulsion System

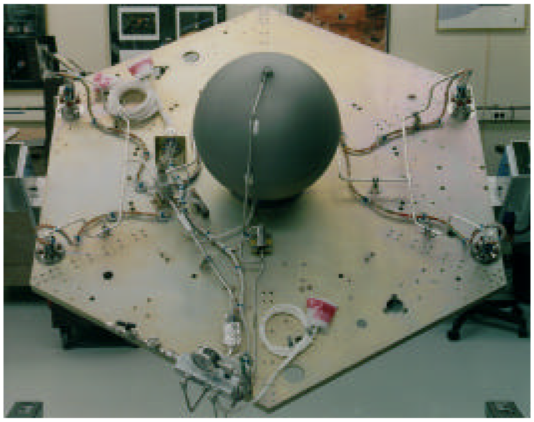
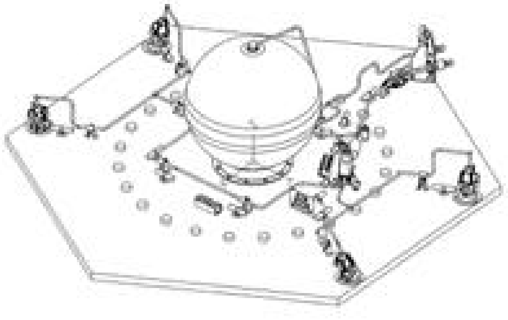


Figure 2 shows the same system in cartoon format, which makes the individual components somewhat easier to see.

Figure 2—EO-1 Propulsion System



Similarly, the GPS IIF propulsion system was able to make use of a previously qualified low cost, light weight titanium tank with elastomeric bladder[3] for positive propellant expulsion. The tank with the bladder secured with a bolted flange[4] had flown on the Athena and Pegasus HAPS launch vehicles, but for a spacecraft application an all-welded version was developed. This required us to repeat the proof pressure cycling and leak before burst demonstration but we were able to analyze the dynamic environments and not repeat vibration testing. The all-welded version has since flown in an upgraded HAPS system, thus validating both the analysis and test programs.

Figure 3 shows the complete propulsion system.

Figure 3—GPS IIF Propulsion System

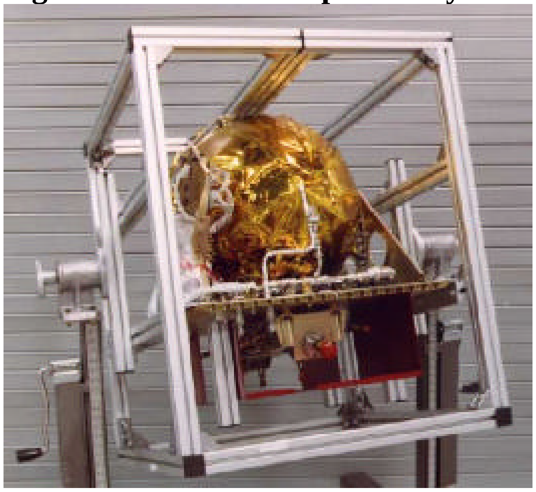
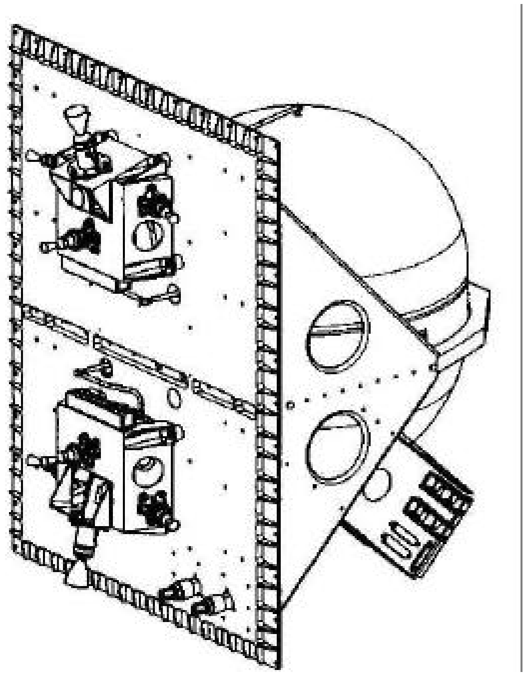


Figure 4 again shows the propulsion system in cartoon format, which is somewhat easier to see.

Figure 4—GPS IIF Propulsion System



Thrusters are usually chosen concurrently with the propellant tanks. The spacecraft operating requirements determines their size and position. Delta-V, drag make-up, ACS, or station-keeping may all require thruster operation and often they provide back-up to other functions such as reaction wheels. As with the propellant tanks, we have a broad array of qualified thrusters from which to choose. Some are listed in Table 1 below:

Table 1—A Selection of Available Monopropellant Hydrazine Thrusters

Model No.	Size (N)	Qualified Life (Impulse/ Pulses)
MR-103C	1	66,720 N-sec 410,000 pulses
MR-103D	1	186,000 N-sec 275,000 pulses
MR-103G	1	79,512 N-sec 205,136 pulses 90,188 N-sec 745,864 pulses
MR-111E	2	260,000 N-sec 420,000 pulses
MR-111C	4.5	260,000 N-sec 420,000 pulses
MR-106E	22	120,000 N-sec 12,405 pulses 125,000 N-sec 186 pulses
MR-107	180-270	426,000 N-sec 26,624 pulses
MR-104	440	693,900 N-sec 1,742 pulses

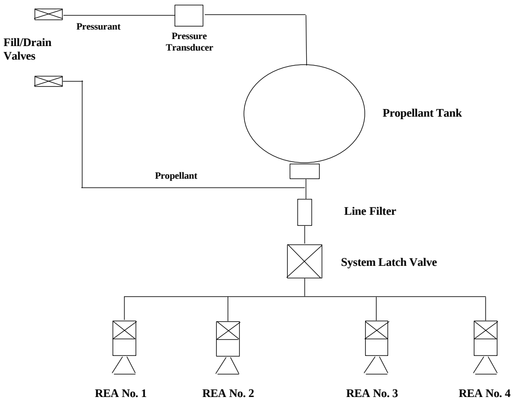
After selecting the thrusters that best serve the purpose, it is important to review the qualified life. Typically thrusters will have “unlimited duty cycle capability”. This means that under usual thermal boundary conditions the thrusters will have been tested for hot restart capability, maximum soak back temperatures at the propellant valve seats and the injector O-rings, and been tested over a variety of duty cycles to verify that none is particularly destructive. This does not mean it is advisable to operate a thruster entirely over a range of untested duty cycles, particularly if one plans to make use of the full qualified total impulse or total pulses or both. The MR-103G 1N thruster is shown in Figure 5. This is one of the lowest thrust and impulse bit hydrazine thrusters currently available, but JPL, PAC, and Perkin Elmer are currently working together to develop a smaller thruster with a faster valve that is capable of producing very small, repeatable impulse bits for use on small satellites.[5]

Figure 5—MR-103G 1N Thruster (Thruster shown is 175 mm from inlet to nozzle and weighs 0.33 kg)

The next critical task facing the propulsion system designer is the selection of the optimal schematic. This is an excellent opportunity to maximize reliability by considering the various failure modes. A pyrotechnic valve, for instance, demands a fuel filter downstream since firing the pyrotechnic valve almost invariably introduces particular contaminants. Pyrotechnic valves, however, are more usually used with launch vehicles and are quite uncommon in small spacecraft since they require special circuitry to activate.

For small spacecraft, a typical propulsion schematic is similar to that shown in Figure 6 for the EO-1 propulsion system. It consists of the propellant tank, service valves (one for the fuel and one for the pressurant), a filter, and a latch valve. The latch valve and dual seat thruster valves satisfies range safety requirements for three inhibits between the fuel and the outside of the spacecraft. A flow restrictor may or may not be required upstream of the thruster valves but is more usually used with larger thrusters to limit water hammer when the propellant is first dropped to the thruster valves after the latch valve is opened. Additional items include telemetry such as pressure transducers and temperature sensors, and thermal hardware (line, tank, valve, and thruster heaters) and control (thermostats or thermistors).

Figure 6—EO-1 Propulsion System Schematic

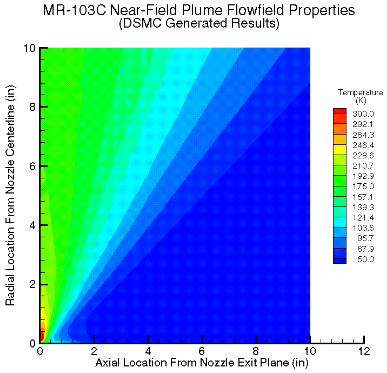


One issue generally not facing the designer of a hydrazine propulsion system is that of material compatibility. Compatible materials are well established,[6] using coupon tests at temperature and pressure extremes, special testing of entire components and systems, and nearly thirty years of on-orbit experience.

On the other hand, hydrazine is perceived as being highly toxic, and there is a strong push to qualify less toxic, or "green" propellants. System design for "green" propellants is similar to that of hydrazine system design, but as we will see in the following paragraphs requires attention to compatibility testing. The benefits of "green" propellants are expected to be: reduced handling and fueling costs; higher fuel density; and improved performance over conventional hydrazine systems with high temperature propellant blends.

Hydrazine decomposes to form nitrogen, hydrogen, ammonia and water. Plume modeling is conducted to determine plume impingement forces and heating on the vehicle structure. The nozzle flow fields are solved using a fully coupled Navier Stokes solution which is then used to obtain the plume flow field via direct simulation Monte Carlo (DSMC) technique. A typical near-field plume is shown in Figure 7. The analysis must show that the thruster alignment results in acceptable impingement forces and heat loads to the vehicle.

Figure 7—Near Field Plume Analysis for a 1N Thruster



EO-1 Pulsed Plasma Thruster System

Pulsed plasma thruster systems are enjoying a resurgence in interest as more and more missions are looking at small satellites and multi-satellite constellation missions. PRIMEX built and flight-qualified the PPT system for the New Millennium Earth Orbiter-1 spacecraft, to be launched in October 2000. Details about the EO-1 mission and the PPT are available elsewhere.[7,8,9]

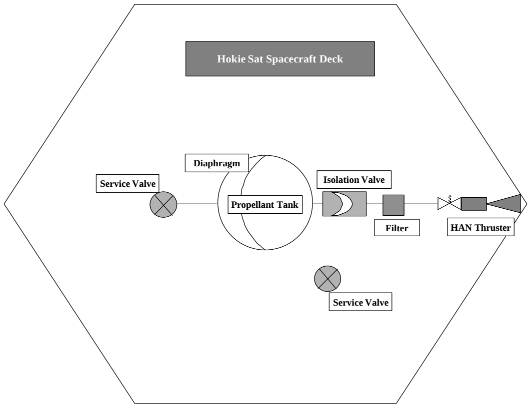
Small "Green" Propellant Blend Systems

HAN-based monopropellants have been demonstrated as a "green" alternative to hydrazine for use in satellite liquid propulsion and ACS systems.[10] Yet, to-date HAN-based monopropellants have only been hot-fired in ground tests (both Sea Level and Vacuum) not flown in space. The first opportunity for an in-space demonstration of a HAN-based propulsion systems arose with the conception of Hokie Sat – Virginia Polytechnic and State University's contribution to the AFRL/AFOSR/ DARPA/NASA University Nanosatellite Program. Hokie Sat is a 15 kg, 18" diameter hexagonal by 12" tall satellite which is scheduled to fly in formation with two other university spacecraft of the same size. Hokie Sat is planned for a six month mission with a maximum life of one year, and will be launched out of the Space Shuttle Payload Bay with the other two formation flyers.

PRIMEX participated with Virginia Tech to establish a HAN-based propulsion system for orbit raising and formation flying uses. ACS is provided by a tethered gravity gradient and torque bars. The overall mass budget for the HAN-based propulsion system was 4 kg (2.4 kg dry). The system was designed using hydrazine propulsion system design know-how. Since the spacecraft was being launched from the Space Shuttle, triple fault tolerances were required on this propulsion system adding to the complexity and weight. Furthermore, HAN-based monopropellants have never flown in space so certification of a new liquid propellant for launch from the Shuttle Payload Bay needed evaluation.

Figure 8 is a rough schematic of the proposed HAN propulsion system. The system – based on hydrazine technology- consisted of a propellant tank, isolation valve, service valves, pressure transducer, propellant valve, thruster, and titanium tubing to connect all the components.

Figure 8—Hokie Sat HAN Propulsion System Design



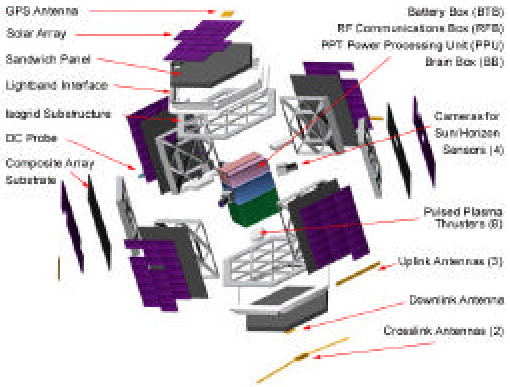
The primary obstacle in developing this propulsion system centered about locating an acceptable, flight-qualified all-titanium propellant tank less than 5" in diameter without an elastomeric diaphragm or bladder. Virginia Tech and PRIMEX both contacted all known propellant tank suppliers only to find that all-titanium propellant tank could be designed and manufactured as a modification to an existing tank, but the costs would be exorbitant. PRIMEX assessed qualifying one of our own development tanks for Hokie Sat, but could not find a solution with the limited funding available. A secondary obstacle entailed qualifying a new monopropellant propulsion system for man-rated spaceflight for literally zero dollars and zero cents. PRIMEX determined that a simple qualification by similarity with hydrazine propulsion systems would be suitable for this application. Safety concerns regarding propellant handling, spacecraft fueling, and maintaining Space Shuttle integrity were also addressed during this support effort. HAN is considered non-toxic since it has no vapor pressure with toxic fumes. Yet protective equipment such as gloves, splash guards, and face shields are necessary since the propellant is highly corrosive. Concerns in handling this propellant at Kennedy Space Center were addressed by designing a pre-fueled propulsion system. This pre-fueled system would then have to be certified by the Department of Transportation for shipping cross country to the integration site.

In the end, a flight-qualified all-titanium propellant tank was not available within the spacecraft budget constraints and Hokie Sat was re-designed to use a PPT like the UW Dawgstar satellite discussed in the following section. This effort has led to a deeper understanding of the remaining efforts necessary to qualify a HAN-based propulsion system for spaceflight on a launch vehicle (either manned or unmanned).

Pulsed Plasma Thrusters for Nanosatellite Formation Flying

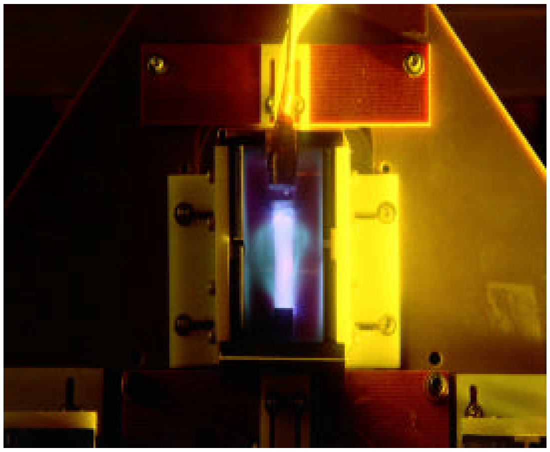
PRIMEX is participating in the development of the PPT propulsion system for the UW Dawgstar satellite, a 15 kg satellite designed as a part of the AFRL/AFOSR/DARPA/NASA University Nanosatellite Program. The UW is designing and fabricating the smallest (public) satellite with full propulsive capability. The primary load-bearing hexagonal structure is an 18" diameter etched isogrid made of aluminum. Attitude determination will be done using a combination of a three-axis magnetometer, three-axis gyro, and CMOS camera based horizon and sun sensing. The satellite uses 23% high efficiency solar cells, L3 Communications T-400 transmitter and CAR-915A receiver, and a patch antenna for uplink, and a loop antenna for downlink. The flight computer is a Hitachi processor, and VxWorks operating system will be used. Figure 9 shows a breakout of the UW Dawgstar satellite and its components.

Figure 9—Exploded view of Dawgstar



The UW Dawgstar satellite also has a GPS receiver, cross-link capability, and eight micro pulsed plasma thrusters. The Applied Physics Lab (APL) at Johns Hopkins University is currently developing an integrated GPS/cross-link system for ION-F through a grant by NASA Goddard Space Flight Center (GSFC). A prototype of one thruster is shown in Figure 10 firing during experimental tests during tests in October 1999.

Figure 10—Prototype PPT Firing at 5J Energy Level



The UW/PRIMEX effort has been an interesting and enriching experience for all involved. At PRIMEX, we are learning about many aspects of satellite design that we have not been previously involved with, such as the guidance, navigation, and control (GN&C). Our many years of experience building satellite propulsion systems brings the team an understanding of what the requirements for space flight hardware are and what the Air Force and DARPA customer's expectations will be to allow the hardware to fly. However, due to the incredibly small budget target of $100,000 per satellite, we have had to modify our usual way of doing business or we would not even be able to come close – graduate student labor notwithstanding![11]

One thing that is truly unique about Dawgstar is that we are developing new technology to enable the mission on many fronts. An example is the miniaturized PPT, as shown in Figure 11.

Figure 11—Dawgstar Miniaturized PPT System (multi-meter and pen are non-flight items)

Performance characteristics of the Dawgstar PPT are described in Table 2.

Table 2—Dawgstar PPT Key Performance Parameters

Characteristic	Value
Input Power	12.5 Watts
Impulse Bit	70 µN-sec
Specific Impulse	500 sec
Energy per Delta-V	17.9 X 10^6 Joule-sec/meter (~2 orders of magnitude higher than cold gas)
Total Mass—8 PPTs and a Power Processing Unit	3.8 kg
Fuel	Teflon
Fuel Mass (Design)	0.12 kg/PPT

New technology development means we do not have the heritage behind us to rely on qualification by similarity. Therefore, the Dawgstar team has found in general that we must still perform the rigorous test and evaluation program that we are accustomed to in the aerospace world, but we had to find a way to reduce the burden of documenting everything to the level that is typically required. The answer in our case seems to be a small, dedicated team of individuals who know basically everything that is happening at a given time on the project. The team still is organized in a traditional way with a lead engineer and others responsible for subsystems, but the key difference is the amount of shared information. There is no such thing as "knowledge is power" and no information hoarding is allowed. The team size is also purposely kept small – essentially the minimum number of individuals required to cover all the subsystems with back-up as appropriate. This flattens the organization and minimizes the number of communication links in the chain. By taking these steps there is no need to request a structural analysis of the impact of a PPT design change on the spacecraft, because the entire team learns of the change at the same time and discusses the action to be taken.

The other important aspect of this arrangement is the dedicated nature of the team. By keeping it small, the budget can be minimized – BUT, and this is one cannot expect these people to be off working multiple other things at the same time. The project should be the single most important thing the team members have to worry about (at least at work). This is a difficult concept in these days of lean, mean staffing. It's very tough for a Director of Engineering to dedicate a key thermal analyst to just one program and not to be tempted to divert this individual to some other jobs that come in. And of course, the reality is that a few outside jobs here and there don't spoil the recipe. But putting someone on three or four simultaneous projects - all of which require focus and understanding of the big picture - is a prescription for disaster.

An example of an issue requiring dedicated, cohesive team effort is planning for the plume. Pulsed plasma thrusters, like all electric propulsion devices, have plume issues associated with their more energetic species and plume constituents. This may include sputtering of spacecraft surfaces, deposition of material on spacecraft surfaces, and electric currents flowing through the plume between spacecraft surfaces. All of these have been shown to be manageable, with proper design. It simply establishes another set of interface definitions, which must be worked out.

Conclusions

We have concluded that cost effective propulsion system design requires:

- Clearly understanding the requirements—what are the mission needs and goals? What are my alternate mission scenarios?
- Minimizing requirements—resisting the urge to write large, cumbersome specifications in favor of a dedicated team approach with responsibilities clearly delineated
- Implementing an Integrated Product Development team with dedicated core members in order to effectively maintain open lines of communication—communication is key both within the core team, with the customer, and with auxiliary members
- Establishing the interfaces and freezing them as early as possible while maintaining flexibility where needed
- Detailed evaluation of the mission plan, comparison with qualification

history, and careful examination of existing analysis and test data

- Surveying the data base—what existing tools, test data, and analysis are available to this project? Which of this information applies and which not, or not directly?
- Planning for additional analysis and test programs
- Fabrication, assembly, test, and flight

In conclusion, we have examined various aspects of propulsion system design. We have reevaluated the process of propulsion system design and related some recent experiences which we hope will help others to maintain quality and reduce cost.

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