A99-31331

AIAA-99-2595

Monopropellant Selection Criteria—Hydrazine and Other Options

Olwen M. Morgan
Dennis S. Meinhardt
PRIMEX Aerospace Co., Redmond, WA

35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
June 20-23, 1999 / Los Angeles, CA

For permission to copy or republish, contact

American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Suite 500
Reston, Virginia 20191-4344

99-2595

MONOPROPELLANT SELECTION CRITERIA--HYDRAZINE AND OTHER OPTIONS

Olwen Morgan (olwen@red.prmx.com)
Dennis Meinhardt (dsm@red.prmx.com)
PRIMEX Aerospace Company
Redmond, Washington

Abstract: Monopropellant propulsion systems offer many advantages for mid-size spacecraft, including simplicity of operation, high reliability, and low cost. Much effort recently has been centered on developing lower toxicity propellants and electric propulsion alternatives, and many of these options show significant promise. This paper will show that hydrazine monopropellant propulsion systems continue to be an excellent choice for many spacecraft applications, and that on-going work to simplify designs and fueling carts has reduced costs and increased simplicity. We will also explore trade studies where some of these other propulsive options are shown to be more appropriate.

Introduction

Since their first flight application in 1966 on Martin Marietta's Titan I launch vehicle's Transtage, monopropellant hydrazine rocket engines with spontaneous catalyst have often been the propulsion of choice. Hydrazine as a propellant offers substantially improved specific impulse over cold gas, and hydrazine systems require half as many tanks, propellant lines, and valves as a comparable bi-propellant system. Versatile and dependable, a monopropellant thruster will operate in steady state, on-pulse, and off-pulse modes.

Nomenclature

ACGIH	American Conference of Governmental Industrial Hygienists
ACS	Attitude Control System
CSD	Chemical Systems Division, United Technologies
DFA	Design for Assembly
DFM	Design for Manufacturing
EHT	Electrothermal Hydrazine Thruster
F	Thrust, N
GEO	Geosynchronous or Geostationary Orbit
GPS	Global Positioning System
HAN	Hydroxyl Ammonium Nitrate
HPB	Hydrazine Propellant Blend
IDLH	Immediately Dangerous to Life or Health
Isp	Specific Impulse, sec
LEO	Low Earth Orbit
LTHG	Low Temperature HAN Glycine
MIT	Minimum Impulse Thruster
MMH	Monomethyl Hydrazine
NIOSH	National Institute for Occupational Safety & Health
NVR	Non-Volatile Residue
OAM	Orbit Adjust Module
OSHA	Occupational Safety and Health Administration
PAC	PRIMEX Aerospace Company
PEL	Permissible Exposure Limit
Pf	Feed or Inlet Pressure, Bar
PPT	Pulsed Plasma Thruster
REA	Rocket Engine Assembly
REM	Rocket Engine Module
TLV	Threshold Limit Value
UDMH	Unsymmetrical Dimethyl Hydrazine

Introduction/History

The advantages of hydrazine as a monopropellant was recognized early on. In 1949, the Jet Propulsion Laboratory funded both engine and catalyst development, and has been credited with the start of the industry[1]. Catalytic hydrazine thrusters and systems have evolved since their first space flight in 1966, becoming less mission specific and more commercially oriented. Over time, PRIMEX Aerospace Company (formerly Rocket Research Company and Olin Aerospace Company) has designed, built, and tested monopropellant hydrazine thrusters for many purposes including some key interplanetary missions. In the year 2000 we expect to ship our 10,000th thruster. We are particularly proud of our contributions to the following interplanetary missions:

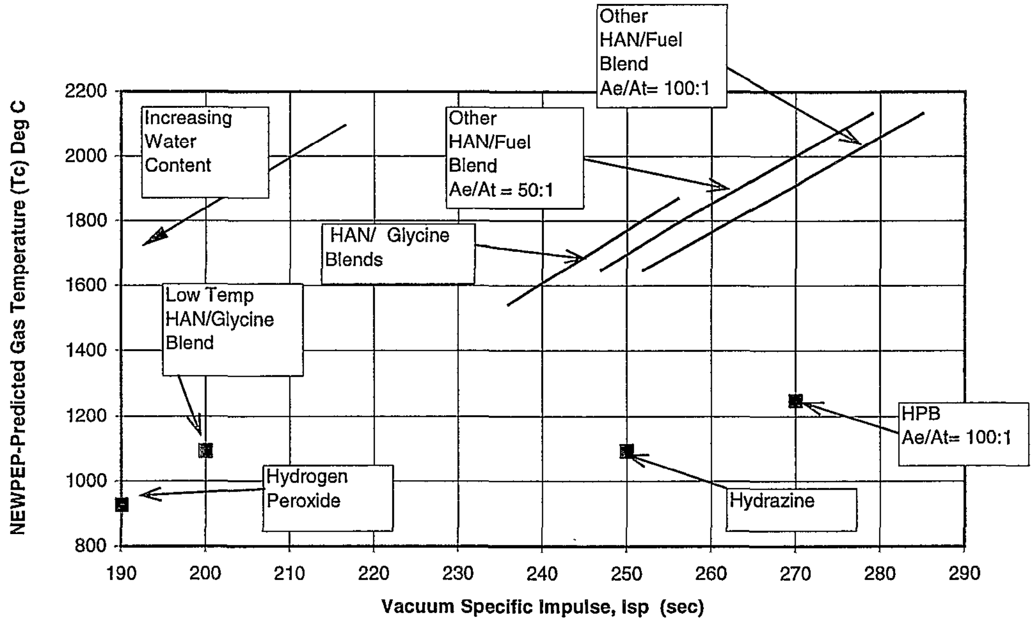
- Viking 1 and Viking 2[2]. Landed on Mars in 1975. Actively guided descent using three 2700N throttleable engines for a soft landing, as well as attitude control and delta-V for the cruise stage.
- Voyager 1 and Voyager 2. Launched in 1977, these satellites are still operational today as they approach the heliopause. The 20N and 445N engines have long since been jettisoned, but the 1N REAs are still functioning nominally.
- Magellan. Launched in 1989 with residual Viking 20N REAs, Voyager 1N REAs, and new MR-104A 445N REAs mounted on four similar but non-identical Rocket Engine Modules, this satellite mapped the surface of Venus for four years. Fuel and valve temperatures were substantially hotter than expected; operation at 140 °C was validated in support of this mission[3].

- Mars Pathfinder. Mars landing July, 1997. MR-111C 4.4N REAs provided attitude control during the cruise stage and to position the satellite to deploy the rover Soujourner.
- Mars Climate Orbiter and Mars Polar Lander. Mars mapping and landing expected in the fall of 1999. Cruise stage REMs for both satellites and dual 300N REMs on the lander for the first actively guided descent since Viking landed on Mars.

While hydrazine has a strong heritage, other propellants and blends offer potential for improved performance and reduced toxicity. Some of these choices include low temperature HAN-based propellants with performance approaching that of hydrazine, high temperature HAN-based propellants with performance approaching that of a bi-propellant system, hydrogen peroxide, and hydrazine blends.

Propellant Choices

For extremely small satellites (10 kg class), propulsion is usually not an option. For slightly larger satellites (100 kg class) with low propulsive requirements, cold gas has typically been used. For launch vehicles, only solid motors and/or liquid bi-propellant stages are adequate to escape earth's gravity. Electric propulsion systems offer high specific impulse, but carry both the cost and weight of the electronics and power conditioning hardware with them. But for a broad band of applications in the middle, catalytic monopropellants offer low cost, flexibility, and a wide thrust range. Figure 1 shows theoretical performance for a range of monopropellant choices. Table 1 shows some physical properties.



Hydrazine

Hydrazine propulsion systems offer the greatest heritage of the candidates with a wide array of choices in qualified thrusters, as well as tanks, latch and pyro valves, service valves, and all the other items needed to assemble a propulsion system. Their reliability is high, its performance is moderate, and its cost relatively low. Its long-term storage stability is excellent.

Compatible dual mode thrusters exist for missions requiring large delta-V, and electrothermal hydrazine thrusters and arcjets offer high performance compatible choices for such applications as geostationary satellite station-keeping. One of the issues associated with hydrazine is its toxicity. While novel fueling approaches can mitigate some of the toxicity concerns, other propellants show promise of reduced toxicity and attendant reduced fueling costs.

Low Combustion Temperature Hydroxyl Ammonium Nitrate (HAN) Blends

Laboratory thruster testing with "low combustion temperature" blends of HAN/Glycine (refer to Figure 1) has demonstrated proof of concept for this new family of environmentally friendly monopropellants. These HAN blends have a higher density and lower melting point than hydrazine, and because there is no toxic vapor pressure, ground support operations are simplified. Additionally, with these HAN-based blends, there are no identified carcinogenic issues.

Table 1—Physical Properties of Some Typical Monopropellant Fuels

Characteristic	Hydrazine, High Purity	HAN-Glycine-Water (Typical)	Hydrogen Peroxide, 90%
Melting Point, °C	1.5	<-35	-11.5
Boiling Point, °C	113.5	Not Measured	141.7
Specific Gravity	1.0	1.42	1.4
Explosion Temp, °C[4]	232	Not available	149
Long-Term Storage Stability	Excellent if kept blanketed with inert gas	Slowly decomposes to form acidic bi-products	Slowly decomposes to form water and oxygen
Toxicity—ACGIH TLV, ppm	0.01	Vapor pressure is water	1.0
Toxicity—OSHA PEL, ppm	0.1	Vapor pressure is water	1.0
Toxicity—NIOSH IDLH, ppm	80	Not Listed	75
Other Precautions	Corrosive, flammable, toxic	Oxidizer, corrosive	Strong oxidizer, corrosive

Figure 2 shows a flight concept HAN thruster firing with the "low temperature" HAN/glycine (LTHG) propellant blend. This thruster was made from the same materials of construction used in a hydrazine thruster. Demonstration tests, like that shown in Figure 3, have shown clean, reliable, stable decomposition/combustion of the propellant in a catalytic thruster. Recently, using a laboratory thruster, performance and life have been demonstrated to 8000 seconds of operation which is suitable for small satellite orbit raising or other ACS missions[5,6]. Further development for flight applications is needed for HAN blends. Also, since there currently are no truly spontaneous catalysts (such as Shell 405 for hydrazine or silver screen for hydrogen peroxide), the use of noble metal catalyst beds for HAN based monopropellants requires preheating to between 200 °C and 320 °C in order to achieve ignition.

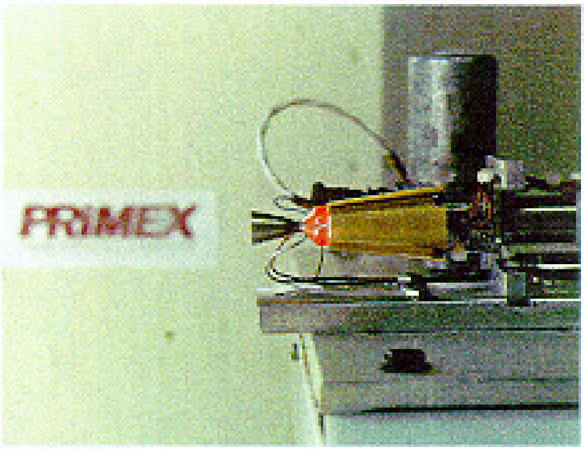


Figure 2—HAN Thruster Firing at Sea Level

High Performing Hydroxyl Ammonium Nitrate (HAN) Blends

High temperature HAN-based monopropellants also show promise. Theoretically, performance will approach that of conventional bi-propellant systems, but without the need for dual tanks, dual valves, dual propellant lines and other duplicate system hardware. The biggest challenge offered by the high temperature blends is their decomposition temperatures, with gas temperatures ranging near 2200 °C. Material choices and ignition methods for monopropellants at these temperatures are limited. Recent ignition testing with a blend of HAN, methanol, and water shows promise for monopropellants with specific impulses of 270 or greater.

Hydrogen Peroxide

Hydrogen peroxide has been proposed for use in small satellites instead of nitrogen propulsion[7]. Laboratory testing using bench-distilled hydrogen peroxide resulted in an impressive display of thrust with few attendant risks to the by-standers. But lack of long term stability of hydrogen peroxide renders it impractical for most satellite applications. However, hydrogen peroxide would appear to have significant applications for monopropellant attitude control thrusters when coupled with a bi-propellant system for launch vehicles.

Hydrazine Propellant Blends

While anhydrous hydrazine satisfies most mission requirements, it is sometimes advantageous to use hydrazine blends. The properties of hydrazine and its decomposition products which may be modified by additives include freezing point, specific impulse, density, and gas temperature. While there are a number of additives than have been effectively blended with hydrazine (including MMH, UDMH, water, and others), selection is usually limited to those additives compatible with spontaneous catalyst. For example, one commonly studied blend is hydrazine/hydrazinium nitrate/water.[8]

This family of blends shows improved performance, suppressed freezing point, and improved density, while maintaining spontaneous ignition with Shell 405 catalyst.

Case Studies

This section examines some typical case studies and the resultant choices, in an effort to illustrate the rationale for making such choices. None of these case studies is a specific application, but all are similar to real-life applications.

Case No. 1:

A small LEO satellite weighing 60 kg with a drag area of 0.40 m^2 and a minimum orbit altitude of 320 km requires drag make-up every orbit. Assuming a mission lifetime of one year, and Solar Max, this results in a total delta-V of 543.3 m/sec. Cold gas propulsion is requested, but assuming a tank with an initial operating feed pressure of 276 Bar (4000 psia) and no repressurization, one needs ~157 kg of GHe and tank, or ~53 kg of GN_2 and tank. The propulsion system weight exceeds or nearly exceeds the mass of the spacecraft and therefore is not practical.

Solution:

A hydrazine system operating at a nominal 24 Bar (350 psia) blowdown, will require approximately 16.7 kg combined propellant and tank mass and will obviate the need for high pressure tanks.

An alternate solution may be a pulsed plasma thruster, which is particularly useful for such applications as drag makeup where low thrust and high performance can be combined to their best advantage. However, PPTs are not yet a mature technology and development costs may be prohibitive, especially for a single satellite.

Case No. 2

A small, science or experimental spacecraft requires orbit raising and ACS. The spacecraft is power and volume constrained, and mission requirements necessitate a minimum of 190 – 200 sec specific impulse. Additionally, simplifications in ground support or handling restrictions could greatly reduce mission recurring cost. A one to five year mission is anticipated with the desire to upgrade to higher performing propulsion options for future missions.

Solution:

Here the propulsion option of choice would include a HAN-based monopropellant like Low Temperature HAN/Glycine (LTHG)[6]. A thruster like the one shown in Figure 2 could complete flight development and reach flight qualification to support near term missions. The improved density of this family of propellants accommodates volume constrained busses; even with the 190 sec specific impulse, the density of LTHG is 1.4 times that of hydrazine resulting in less volume needed than for a conventional propulsion system. Conventional catalytic HAN thrusters can be used for ACS maneuvers, or a warm gas ACS system with a single catalyst bed and warm gas thrusters provides an alternative. Finally, with continuing development of this technology, higher performing systems (up to 270 sec Isp) may be available in the future.

Case No. 3

Small interplanetary spacecraft require a large delta-V during planetary encounters. After the planetary encounter, fine pointing requirements are required for imaging and payload deployment.

Solution:

A small dual mode engine provides delta-V. Monopropellant hydrazine thrusters such as the MR-103-series 1N REAs or the smaller Minimum Impulse Bit thrusters (see brief description later in this paper) provide fine pointing and balance during the delta-V burn. The monopropellant thrusters are used when small impulse bits and flexible duty cycles are needed.

System advantages include high performance during the relatively large delta-V burn afforded by the dual mode engines which typically have specific impulses on the order of 300 sec, and a common fuel for both the dual mode engine and the monopropellant REAs.

Case No. 4

A large geosynchronous satellite requires orbit raising after launch, weekly station-keeping, and reaction wheel desaturation maneuvers.

Solution:

There are several solutions to this problem including bi-propellant thrusters, electric propulsion and other options. Hydrazine is a particularly suitable option, however, because of its versatility. Using a dual mode (N_2O_4/N_2H_4) engine provides rapid ascent and good performance for orbit raising maneuvers. Residual hydrazine in the hydrazine tanks is then used for the remaining propulsion requirements. Generally, station-keeping exercises are performed by electrothermal hydrazine thrusters[9,10] or arcjets[11], which will provide 1.5 to 3 times the specific impulse respectively of a conventional catalytic thruster, while ACS and momentum dumping are performed by the conventional REAs. The conventional catalytic thrusters are qualified for on-pulsing, off-pulsing, and steady state operation. The EHTs are qualified for off-pulsing and steady state operation, while the Arcjets operate only in steady state mode.

The EHTs and Arcjets derive their power from the solar panels (by way of the batteries and power conditioning units), so much of the performance gain over the simple catalytic thrusters is renewable—i.e. it is not part of the launch mass.

The ability to operate in both pulse mode and steady state is a clear advantage of a monopropellant thruster over a bi-propellant thruster and over just about any sort of electric propulsion. While many bi-propellant thrusters operate in pulse mode, some have significant restrictions. Monopropellant thrusters can also provide significantly lower thrust than bi-propellant thrusters. All else being equal, lower thrust engines will produce smaller impulse bits, which in turn will result in finer maneuvering capability on the vehicle.

Industry Improvements

Many changes have been made in monopropellant thruster design and manufacture since the Transtage REM first flew in 1966 that have improved reliability and diminished cost. Some of these improvements are discussed in the following paragraphs.

Design for Manufacturing/Design for Assembly

Early rocket engine design efforts were focused on mission success and performance. Nearly all the missions were government funded, and there were fewer missions. As we have evolved from a primarily science and government driven industry to a commercially based space effort, engine design has also evolved. Not only have we built on a substantial heritage of both qualification and flight data, but we have been able to take advantage of such tools as Design for Manufacturing/Design for Assembly (DFM/DFA). For instance, the MR-103C 1N Rocket Engine Assembly, shown below in Figure 3, has been largely replaced by the MR-103G 1N Rocket Engine Assembly shown in Figure 4.

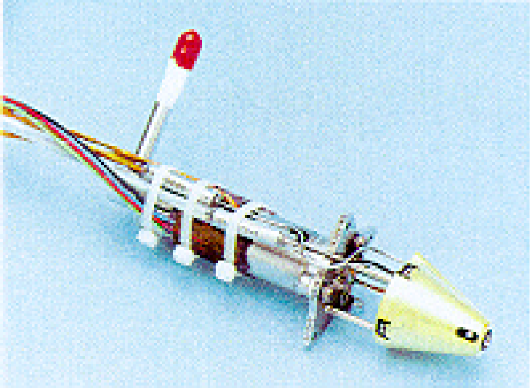


Figure 3—MR-103C/D 1N Rocket Engine Assembly

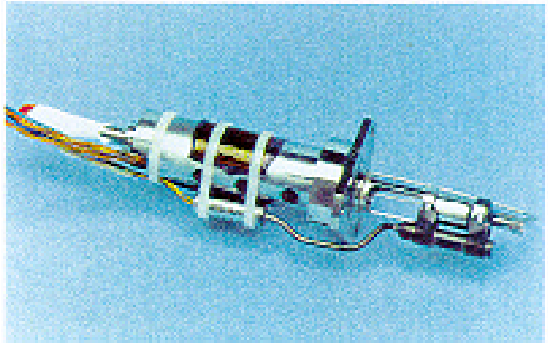


Figure 4—MR-103G 1N Rocket Engine Assembly

While the two engines are functionally interchangeable, considerable cost savings has been achieved by piece part reduction, process simplification, and by simplification of acceptance testing. Without the gold plated heat shield, the MR-103G requires approximately 3 Watts more catalyst bed heater power during pre-firing warm up sequences, but advances in battery and solar panel technology have made 3 Watts trivial for all but the interplanetary missions. Table 2 illustrates substantial part and processes count advantages of the MR-103G catalytic decomposition chamber design over that of the MR-103C/D.

Table 2—Comparison of MR-103C/D Thruster Design with MR-103G Thruster Design

Thruster Design*	MR-103C(D)	MR-103G
Number of piece parts	22 (24)	7
Processes	e.b. weld, e.b. braze, furnace braze, TIG weld	Furnace braze, TIG weld

* Catalytic Decomposition Chamber Design (Including the Injector)

Table 3 illustrates that for all but the most stringent applications, the MR-103G 1N REAs are fully interchangeable with the standard MR-103C and the longlife MR-103D 1N REAs. Since they cost approximately half that of the MR-103C/D REAs this is a distinct advantage, especially for spacecraft built in significant quantities. MR-103G 1N REAs are currently in use in LEO for the Iridium® constellation and in GEO applications for the A2100™ communications spacecraft.

Table 3—Comparison of Qualification Test Programs, MR-103-series 1N REAs

Model No.	Total Impulse N-sec (lbf-sec)	Total Pulses
MR-103 (Voyager)*	68,721 (15,450)	410,153
MR-103D (Longlife)	183,876 (41,339)	275,028
MR-103D (Longlife)	186,051 (41,828)	244,695
MR-103D (Longlife)	125,714 (28,263)	210,238
MR-103G (LEO)	79,512 (17,876)	205,136
MR-103G (GEO)	90,188 (20,276)	745,864

* The Voyager qualification test series, which included 112 starts with a 4.4 °C catalyst bed, forms the basis for the qualification of the MR-103C standard 1N REA. The MR-103D 1N REA features a unique stepped capillary tube design which limits NVR build-up and prolongs life.

Similarly, the 20N Rocket Engine Assemblies PAC makes for most spacecraft (including GPS Block IIR and IIF) have benefited from design simplification. The MR-106-series 20-40N REAs were originally designed for launch vehicle applications such as the Centaur upper stage. However, the design proved to be sufficiently rugged and long-lived that by adding such features as catalyst bed heaters, valve heaters, and telemetry, the engines could also be made suitable for spacecraft applications.

PAC's MR-107 130-300N class of REAs is also normally used for launch vehicle applications. Multiple piece parts, hand-machining, and multiple bedplates were a feature of the Transtage design: the MR-107 series REAs incorporated design simplicity from their inception. Similar in design to the MR-106 REAs, they feature an axial bed design with three injection elements, a spontaneous upper bed and non-spontaneous lower bed. By building flexibility into the design, this class of engines spans a broad range of thrust. The MR-107N REAs on Mars Polar Lander (294N at Pf=27.6 Bar) will be used for the first actively guided descent onto the Martian surface since the Viking Landers.

The 2-4.5N REAs are the next class of engines PAC is working to simplify. As with the 1N REAs, the objective is to maintain the core features of the design, while simplifying manufacture to achieve price reductions in the range of 50% over the standard model. Development testing is complete, and qualification testing is scheduled to finish in the first quarter of 2000.

Also in need of further development are hydrazine thrusters for miniaturized applications. JPL, EG&G Engineered Products, and PAC are currently working to develop a Minimum Impulse Thruster, or MIT[12]. The MIT pairs EG&G's ultra-small, ultra-fast valve with the MR-103C thruster, and will provide nearly 1N steady state thrust, but substantially smaller impulse bits for fine pointing control and reaction wheel back-up than the MR-103C thruster paired with its standard valve. Testing has begun, with a completed design to be ready for applications such as the Mars Micromissions slated for early in 2000. The next step is to apply DFM/DFA principals to the thruster portion of the design (as opposed to just the valve), and develop and qualify a truly miniaturized hydrazine thruster.

While the examples associated with this section have been primarily monopropellant hydrazine thrusters, DFM/DFA principles can readily be applied to other thruster designs. Thrusters built to date at PAC for Hydroxyl Ammonium Nitrate (HAN) development and test with catalytic decomposition ignition have used similar designs to those developed for the hydrazine thrusters.

Building the Data Base

One of PAC's first "off-the-shelf" thruster procurements was Ball Aerospace's procurement of MR-111C 4.5N REAs for the Radarsat I program in 1991. Before that time, each individual thruster procurement resulted in a mission-specific part number, and a mission-specific acceptance test (hot fire) sequence. However, if the performance of the engines is well understood, acceptance testing is only necessary to characterize individual performance (thrust) and verify workmanship. Accordingly, the practice began of keeping a running tally of the various hot fire duty cycles that have been fired for an individual model number, and the key results (typically end of run thrust or impulse bit, end of run specific impulse, and end of run chamber temperature). For the MR-103C/D 1N REA series, this tally runs to some 240 line items, representing 240 different duty cycles and pressures, and not including qualification testing. Some slight overlap occurs because steady state sequences are tallied for each production series, as this helps to determine whether there are any long term shifts that might indicate manufacturing or test differences. If impulse bit repeatability, centroid, heat-up transients or other parameters are of interest to a customer, the full sets of reduced data are maintained on file and are readily accessible by consulting the consolidated data base.

Similarly, some analysis tasks are avoided by using existing analyses to compare conditions. Both thermal and structural requirements can be readily compared with prior analyses, and in many cases existing analysis and test results will envelope new requirements, thus avoiding both test and analysis costs.

System Considerations

Modular systems provide many advantages to the end item user. An example of a modular system for a launch vehicle application is the Athena Orbit Adjust Module[13], PAC developed as an Athena partner together with Lockheed-Martin, Thiokol, and CSD. Working with Keystone Engineering to develop a low cost titanium tank, the PAC OAM was built at a fraction of the cost of prior similar systems. Cost savings were achieved through tank development, use of common parts, streamlining of system assembly tasks, and use of such principles as concurrent engineering and DFM/DFA. The incorporation of the OAM allowed the use of high reliability solid motors in the first stage, by providing attitude control, improved orbit insertion accuracy, payload deployment and collision avoidance. All Athena launches have used the PAC OAM and all OAM performance has been "nominal". Plans are in place to upgrade the OAM to a dual mode system[14] as soon as a need is identified.

Capitalizing on the Athena system, PAC was able to slightly revise the bladder tank design for use on the GPS IIF program[15]. Low cost, heritage components including the MR-111C 4.5N and MR-106E 20N REAs, and purchased parts such as the latch valves, service valves, pressure transducers, filters, and thermal control have been integrated onto an aluminum iso-grid structure that becomes part of the vehicle's structure. The modular design was an excellent example of concurrent engineering: PAC engineers worked very closely with Boeing engineers during all phases of the program.

Fueling

PAC has developed and used a modular fueling cart capable of loading fuel, pressurization, and off-loading if necessary. Its main advantage is that it is returned to the plant fully sealed, and requires no decontamination, hydrazine processing, or hydrazine sampling at the range. Use of this cart has been demonstrated at Kourou, Cape Canaveral AFS, Vandenberg AFB, and Wallops Island. This same approach may be used for any propellant, although compatible materials must be selected throughout.

An alternative to fueling at the range is a pre-fueled module. DOT-rated containers are available that are capable of containing small propulsion systems. For small satellites with modular propulsion systems, this would appear to be the fueling method of choice. Using a bladder or diaphragm tank, the system could be shipped fueled and then pressurized at the range.

Conclusions

Catalytic monopropellant rocket engines can provide propulsion for satellite and launch vehicle applications either alone, or in combination with dual mode and electric propulsion thrusters. Hydrazine is often the propellant of choice, but other substances and blends offer features such as depressed freezing points, reduced toxicity, increased density (with the potential for higher Isp for a given volume) or less complicated fueling techniques. In response to a general need for reduced cost, standard parts, and increased simplicity, rocket engine technology has evolved. Hydrazine rocket engines and systems are "off-the-shelf" or very nearly so, now. Further work is needed to provide the same kind of heritage and associated system design with alternative fuels.

References

---

[1] Schmidt, Eckart W., Hydrazine and Its Derivatives, John Wiley and Sons, 1984.

[2] Morrisey, Donald C. "Historical Perspective: Viking Mars Lander Propulsion". Journal of Propulsion and Power Volume 8 No. 2, March-April 1992, Pages 320-331.

[3] Constanza, Robert A., "Simulated Mission Testing of a 0.2 lbf Magellan Monopropellant Thruster", AIAA Paper 92-3804.

[4] Sutton, George P. and Ross, Donald M., Rocket Propulsion Elements, John Wiley and Sons, 1976.

[5] Meinhardt, D.S. and Christofferson, S., "Performance and Life Testing of Small HAN Thrusters". AIAA Paper 99-2881.

[6] Urban, M. Gruner, Morrissey, Sneiderman, "Investigation of Propulsion System Requirements for Spartan Lite". 12th Annual Conference on Small Satellites, SSC98-VIII-5.

[7] Whitehead, John C. "Hydrogen Peroxide for Smaller Satellites". AIAA/USU Conference on Small Satellites, 1998. SSC98-VIII-1.

[8] PRIMEX Aerospace Company "Hydrazine Handbook".

[9] McKevitt, F.X., "Design and Development Approach for the Augmented Catalytic Thruster (ACT). AIAA Paper 83-1255.

[10] Roberts, C.R., "Life Demonstration Test of an Uprated Augmented Catalytic Thruster", AIAA Paper 87-0996

[11] Smith, R.D., Roberts, C.R., Davies, K., and Vaz, J. "Development and Demonstration of a 1.8 kW Hydrazine Arcjet Thruster. AIAA Paper 90-2547.

---

[12] Parker, Morgan, Thunnissen, Dan, Blandino, John, and Ganapathi, G. "The Preliminary Design and Status of a Hydrazine Millinewton Thruster Development". AIAA-99-2596.

[13] Wilson, A.C., and Connors, J. J. "Low Cost Liquid Upper Stage for the Lockheed Launch Vehicle". AIAA-94-3378.

[14] Hearn, H.C., Wilson, A.C., "Evaluation of Dual Mode Orbit Adjust Module for Enhanced LLV Performance". AIAA-95-2839.

[15] Swink, Donald, Morgan, Olwen, and Robinson, John. "Design and Analysis of a Low Cost Reaction Control System for GPS IIF". AIAA-99-2469.