

NASA/CR—1998-206608



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March 1998

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Prepared for the
COSPAR Colloquium on Scientific Microsatellites
cosponsored by the Committee on Space Research, International Academy
of Astronautics, and the National Science Council (NSC)
Tainan, Taiwan, ROC, December 14–17, 1997

Prepared under Contract NAS3-27186

National Aeronautics and
Space Administration

Lewis Research Center

March 1998

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PROPULSION OPTIONS FOR PRIMARY THRUST AND ATTITUDE CONTROL OF MICROSPACECRAFT

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ABSTRACT

Order of magnitude decreases in the size of scientific satellites and spacecraft could provide concurrent decreases in mission costs because of lower launch and fabrication costs. Although many subsystems are amenable to dramatic size reductions, miniaturization of the propulsion subsystems is not straightforward. There are a range of requirements for both primary and attitude control propulsion, dictated by mission requirements, satellite size, and power restrictions. Many of the established propulsion technologies can not currently be applied to microspacecraft. Because of this, micro-electromechanical systems (MEMS) fabrication technology is being explored as a path for miniaturization.

INTRODUCTION

During the last few decades, increasingly larger scientific satellites have been built and launched to provide powerful research tools. The expense of these large spacecraft is such that only one or two satellites can be built per decade. The single large spacecraft approach brings with it the risk that failure of the satellite to be deployed leaves a large void in scientific research.

In order to spread the risk of deployment and to reduce the costs associated with satellite launch and operation, it is imperative to reduce satellite size by at least an order of magnitude. This sharp reduction in size has far reaching consequences for all spacecraft subsystems, including the propulsion. Virtually all current spacecraft utilize propulsion systems in one way or another. The propulsion subsystem can account for anywhere from 20 to 90 percent of the total spacecraft mass. Within limits, propulsion system dry mass can be scaled down. However, for conventional systems, both electric and chemical, performance typically decreases with decreasing size. In most cases, therefore, propellants will occupy a larger proportional mass and volume for smaller satellites than for larger satellites with similar ΔV requirements. Electric propulsion systems are state-of-the art for primary propulsion for larger spacecraft with high ΔV requirements. Microsizing spacecraft and spacecraft subsystems, however, requires a re-evaluation of the propulsion system selection with spacecraft characteristics such as required mission ΔV , available propulsion system mass, available power, and plume contamination issues as prime criteria.

The simplest method to reduce weight, size, and cost of propulsion systems is to accept single string design (with few exceptions) (Santo 1996). Because a large fraction of launch costs consists of safety procedures surrounding the storage, handling, and loading of toxic and/or carcinogenic propellants used by established propulsion systems, additional cost savings can be obtained by utilizing environmentally safe propellants, with better performance and/or storage characteristics than existing monopropellants.

To enable an order of magnitude reduction in spacecraft size while retaining mission capabilities, nothing less than revolutionary developments in propulsion technology are needed. Such developments have not been forthcoming, most likely because the emphasis on microspacecraft is just starting. The need for innovative technologies is graphically represented in Figure 1. Some existing spacecraft are shown, from the 12 kg, 0.006 kW Microsat-I (no propulsion) to the 10.8 metric ton, 4.3 kW Hubble. At the low mass/power end of the graph, an area exists where, depending on mission requirements, spacecraft propulsive needs may be met with scaled down versions of conventional propulsion systems. The boundaries of this “technology barrier” are not well defined.

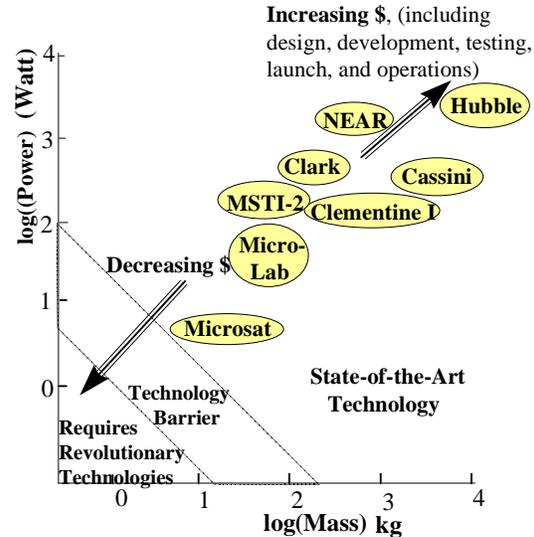


Figure 1. Technology Requirements for Microspacecraft

One technology that has the potential to revolutionize micropropulsion is a manufacturing technique that utilizes etching and photolithography, such as used in computer chip manufacturing. Both chemical and electric propulsion concepts could benefit from this micro-electromechanical systems (MEMS) technology. Some propulsion requirements that can not be met with propulsion systems made with conventional manufacturing, could be replaced with MEMS manufactured hardware, such as MEMS resistojets or MEMS monopropellant thrusters. A major advantage of applying MEMS technology at this stage of development appears to lie in the cost savings that can be obtained with batch fabrication. An additional advantage is the potential of chip integration of thrusters with computing, communication, and sensing equipment, allowing low cost, batch fabricated microspacecraft. Several programs have been initiated to investigate MEMS technology for propulsion and power applications. For very low mass/power requirements, MEMS machined conventional concepts would not be sufficient and innovative new concepts need to be developed.

A number of papers have recently been written on the subject of propulsion options for microsatellites. De Groot and Olesen (1996), in a review paper covering chemical propulsion options, categorize systems by thrust level without regard to satellite size. Thrust level deemed relevant for micropropulsion ranged from 10^{-6} to 10 N. Several mission scenarios were described in that paper for spacecraft from 20 to 350 kg mass. An excellent review of microspacecraft propulsion options was given by Mueller (1997). Mueller defined microspacecraft as spacecraft of mass roughly smaller than 20 kg, power smaller than 0.02 kW, and dimensions approximately 0.4 m on the side. For scaling he assumed a power density of 0.001 kW/kg and subsequently subdivided these spacecraft by evaluating whether scaled down versions of conventional technology could be utilized or whether alternate (e.g. MEMS) technology need to be applied.

This paper reviews propulsion systems currently available or in development stages nearing completion. Critical performance data for minimum thrust level of full size propulsion systems are given as well as estimates of performance for a strongly scaled down version. Typical mission criteria are reviewed and the most likely propulsion systems for the microspacecraft mission are analyzed.

MICROSPACECRAFT PROPULSION REQUIREMENTS

Many of the impulse requirements laid out in this section were generated during a micro-propulsion workshop and are shown in Table 1 (JPL 1997). Typical science missions envisioned to be executed with micro-spacecraft are single spacecraft planetary or asteroid missions, or multiple spacecraft observer clusters. For many micro-spacecraft missions, the primary velocity increases (ΔV increments) required during spacecraft maneuvers are equal to those of larger spacecraft. The primary ΔV s refer here to large changes in orbit parameters (e.g. orbit transfer, repositioning, deorbit, and planetary capture/escape). Secondary ΔV refers to smaller changes in orbit parameters, such as orbit maintenance (e.g. stationkeeping and drag makeup), adjusting orbit parameters (phasing of a single or multiple spacecraft), or attitude control [ACS] (e.g. three axis control, momentum/reaction wheel dumping, or spacecraft spin control.). Microspacecraft primary ΔV missions call for lower thrust levels corresponding to the spacecraft mass and power availability. Microspacecraft secondary ΔV missions will additionally call for small impulse bits to achieve similar secondary ΔV increments as larger spacecraft. In some instances, the widely varying primary and secondary ΔV requirements of each mission type can only be met by a combination of different primary and secondary propulsion systems, whether of impulsive or long thrust duration (e.g. electric propulsion).

Table 1. Typical Microspacecraft Propulsion System Requirements (JPL Workshop):

Mission	Primary ΔV /Duration (m/s)/yr		ACS ΔV /Duration (m/s)/yr	Thrust (mN)
	Impulsive	Non-impuls.		
Vesta Rendezvous	3400/4.3		2.5 * S/Cmass	0.5 * S/Cmass
		7000/2.7	2.5 * S/Cmass	0.5 * S/Cmass
Europe Orbiter	2500/4.8		5.0 * S/Cmass	0.5 * S/Cmass
	945	5500/5.8	5.0 * S/Cmass	0.5 * S/Cmass
DS-3 Interferometer	---	---	100-300/0.5-1.0	
Earth Observing Clust.	500/5.0	550/5.0	5.0 * S/Cmass	0.5 * S/Cmass
Heliocentric Cluster	1400/3		6.0/1-2	1250
	(from GTO)	3000/3	6.0/1-2	1250
		(from LEO)		

Clusters of small spacecraft are intended to replace single large observation spacecraft. Virtual apertures created by multiple, formation flying spacecraft have the potential to obtain signals that would be impossible to obtain with a single large spacecraft, and probably at a much lower cost. These clusters could be launched from either a mothership or from a launch vehicle. In both cases, most of the primary propulsion requirements could be performed by the launch vehicle. Primary propulsion might be needed for a system that 'piggy-backs' on an existing launch vehicle and requires orbit raising, or for an interplanetary or asteroid rendezvous mission. Typical mission requirements for impulsive thrusters are 1.2 to 4.0 km/s. The same missions undertaken with electric thrusters require 2.2 to 7.0 km/s. Depending on the scope of the planetary observation, ACS functions can be done by either electric or impulsive propulsion systems and could possibly be performed by one of the primary propulsion systems. For earth or planetary clusters, propulsion could be used to maintain formation using non-Keplerian orbits (Janson 1994). Continuous thrust is used to assume the non-Keplerian orbit. ΔV s for providing this non-Keplerian orbit depend on

spacing and operational altitude. Propulsion for stationkeeping is also required to offset disturbances. For deep space interferometer missions it is assumed that the launch vehicle delivers the spacecraft in earth escape solar orbit. The only primary propulsion required is for “aperture filling” maneuvers, where the distance between spacecraft varies from 0.1 to 1.0 km. For a 3-axis stabilized spacecraft, the ΔV requirement would be 100 to 300 m/s for a 0.5 to 1 year mission.

For large spacecraft missions requiring large primary ΔV , the reduced wet mass provided by an electric propulsion system makes it attractive compared to impulsive chemical system. Figure 2. shows the ratio of propellant mass versus spacecraft dry mass (including propulsion system dry mass) as a function of specific impulse for two values of ΔV , 1 km/s and 5 km/s. A cold gas system (75 s Isp) would need 890 times the spacecraft mass in propellant in order to achieve a ΔV of 5 km/s. A high performance bipropellant engine (315 s Isp) would require a ratio of propellant mass to spacecraft dry mass of 5.8, and an arcjet (600 s Isp) would only require a ratio of 1.3. For PPTs (1500 s Isp) and Ion thrusters (3200 s Isp), these ratios would be approximately 0.4 and 0.19, respectively. Issues that need to be addressed to make a number of electric propulsion systems amenable to microspacecraft are power requirements, efficiency, weight of the propulsion system dry mass, and contamination issues. For several classes of missions, such as low earth orbit (LEO) missions, and major constellation maneuvers, thrust level is also an important consideration.

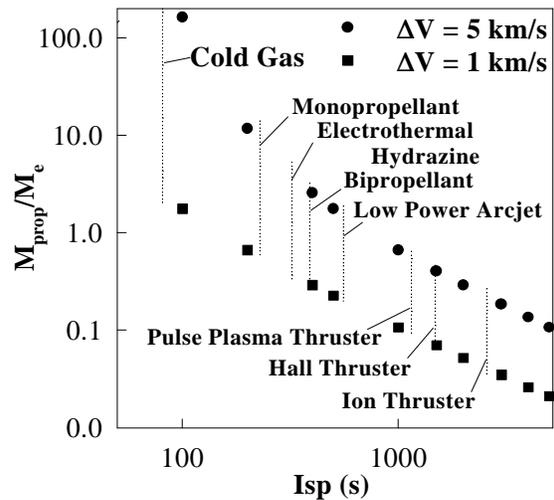


Figure 2. Propellant Mass to Achieve a ΔV of 1 and 5 km/s as a Function of Isp.

In some, but not all cases the electric propulsion system will require a longer trip time. For instances where burn time must be low (e.g. thrust high) such as ballistic planetary capture, an impulsive system must be used. Secondary ΔV missions can also require large ΔV s. For these cases electric propulsion can save mass as long as slew rate and pointing accuracy requirements are within the system’s capability. The availability of power on the microspacecraft can impact propulsion system selection. For primary propulsion, the payload is usually inactive, freeing up a large amount of power for electric propulsion. However, during secondary propulsion the payload is normally active, reducing the power availability unless the payload’s reserve system can be used (e.g. batteries for stationkeeping of communication satellites). For very low power spacecraft with primary and/or secondary propulsion requirements power capability must be added or an impulsive system used.

STATE-OF-THE-ART PROPULSION TECHNOLOGIES

Chemical. Of the chemical propulsion systems frequently used in spacecraft, cold gas propulsion systems have the lowest complexity and cost. They can provide highly repeatable, extremely small impulse bits for accurate orbit maintenance and attitude control. However, these systems also have the lowest performance in terms of specific impulse (Isp) and total impulse for a given volume. Cold gas thruster performance likely scales better than the performance of most conventional chemical and electric thrusters. However, the low Isp still leads to storage problems. Leakage can

become a liability for long mission durations, both in terms of attitude control (leaking gas could exert a force), and in terms of lifetime. For minor primary propulsion functions and ACS tasks with a relatively short mission duration and a low overall impulse, cold gas systems may work well. For these applications, the simplicity and low dry mass are a benefit, despite the low Isp. The minimum obtainable impulse bits are on the order of 10 $\mu\text{N}\cdot\text{s}$.

Solid propellant thrusters are frequently used for orbit insertion. These thrusters are simple, reliable, and have a high propellant density, giving high density specific impulse. Because of the high density, easy storage (no leakage, no valves and/or regulators), and relatively high performance, solid propellants could become prime candidates to perform primary propulsion functions on microspacecraft. The main disadvantage is the lack of restartability which limits the use to a single, high impulse burn for each thruster used. Together with issues such as packaging, restartability need to be addressed before alternate propulsion functions are considered.

The most common propulsion system found on current spacecraft is the hydrazine monopropellant system. Hydrazine monoprops are among the best currently available candidates for micropropulsion applications for spacecraft larger than 10 kg. The storability, catalytic ignitability, restartability, and good performance of monopropellant systems are sufficient reasons to select this concept for some primary propulsion applications and many orbit maintenance functions. The system simplicity has proven to provide reliable performance for many spacecraft. The simplicity also allows miniaturization of all components without a large reduction in performance. Because of the liquid storage, leakage is less of a problem than for cold gas systems. Some loss in performance will occur when scaling down as the result of larger proportional wall area which increases heat losses and viscous losses. However, the performance is expected to only be slightly lower than larger versions. The smallest currently available hydrazine thruster can operate at a thrust level of 0.19 N with a 206 Isp. Although additional research is needed, catalyst beds can be created with sub-millimeter characteristic dimensions. Lower limits on flow velocity through the catalyst bed and heat transfer out of the catalyst will determine the smallest possible impulse bit. Impulse bit delivery spans a wide range, from 10 $\mu\text{N}\cdot\text{s}$ upwards. Issues that have to be addressed are similar to its larger version, namely material compatibility and propellant safety and handling issues. Some power is required to pre-heat the catalyst bed.

Hydrazine/nitrogen tetroxide (NTO) or monomethyl hydrazine/NTO bi-propellant thrusters have the highest performance of chemical spacecraft propulsion systems. Because of their high performance, they are frequently used for high impulse primary thrust applications, such as orbit insertion, orbit raising, divert propulsion or interplanetary propulsion. The large dry mass required can only be justified for high total impulse applications. Because of the large proportional dry mass, bipropellant systems do not lend themselves well to being downscaled. An additional problem of small scale bipropellants is the difficulty in obtaining thorough propellant mixing within the small combustion chamber. This causes ignition delays and reduced performance. The smallest available bipropellant thrusters operate at a thrust level of 2 N with an Isp of 265 s compared to an Isp of 315 s for a 100 N thruster.

Electric. Three classes of electric propulsion devices are currently in use or near being used in flight. These types are referred to as electrothermal, electrostatic, or electromagnetic devices, depending on the principle by which the working fluid is accelerated to provide thrust. Electrothermal thrusters create a high temperature fluid which provides a driving force by acceleration through a conventional nozzle. The thermal energy of the fluid is partly converted to

kinetic energy. Electrostatic thrusters provide thrust by accelerating a charged plasma by means of a static electric field. Electromagnetic thrusters apply an electromagnetic field to accelerate an electrically charged plasma. This electromagnetic field can be self-induced or externally generated.

The least complex electric propulsion system available is the resistojet. In a hydrazine resistojet, the heat of the products of hydrazine, decomposed in a catalyst bed, is resistively augmented in a heating coil. The increase in performance over monopropellants can range to 80 s, but this requires 0.3-0.4 kW of electric power. In scaling this concept to smaller size, previously stated concerns about the propellant flow rate and heat transfer are valid. In addition, power becomes scarcer when miniaturizing spacecraft, such that power consumption needs to be considered. Hydrazine resistojets require too much power for microthrust applications.

Arcjets, also an electrothermal propulsion concept, operate by directly heating the propellant (usually hydrazine passed through a catalyst bed to create hydrogen and nitrogen) with a stationary arc in/near the nozzle contraction. The primary application of arcjets has been stationkeeping of large satellites. Up to 600 s Isp has been demonstrated with 2.2 kW systems. Low power arcjets perform well at 0.5 to 0.75 kW. Below 0.5 kW, the performance decreases (Sankovic and Jacobson 1995) and current technology does not allow operation at microspacecraft power levels.

Ion thrusters are electrostatic propulsion devices. In an ion thruster, a plasma is created from a propellant (usually xenon) by means of an electrical discharge in the discharge chamber. The plasma is accelerated in an electrostatic field created by a set of ion grids (ion optics) placed at the exit of the thruster. After the ions leave the thruster, a neutralizer cathode is used to return electrons to the plasma. This prevents a negative charge from building up on the spacecraft. The smallest ion thrusters available are the 10 cm diameter British DERA T5 and the DASA RITA thruster. A 13 cm diameter Hughes XIPS thruster with an Isp of 2585 s, overall efficiency of 51.3%, and power of 300 Watt was launched on the ASTRA 1G satellite on December 3rd, 1997. An experimental ion thruster was launched on-board the Japanese ETS-VI, but the spacecraft failed to reach its intended orbit and the test program was severely shortened. Ion thruster loss mechanisms, such as recombination, are dominated by wall effects. Reducing the physical size will therefore reduce the efficiency and Isp. Ion thrusters could be considered for microspacecraft propulsion if issues regarding these wall losses, plume neutralization, and high voltage arcing can be resolved.

Another electrostatic concept is the Hall effect thruster. Xenon thrusters of this type have been used on Russian spacecraft (Meteor, a.o.) for orbit-raising, drag make-up, and North-South Station Keeping (NSSK). Russian Hall thrusters, such as the Stationary Plasma Thruster (SPT) and the Thruster with Anode Layer (TAL) have been adapted and qualified for American standards in a collaborative effort to develop a NSSK device for use on geostationary satellites. The SPT-100 typically provides 80 mN thrust at an Isp of 1600 s and 48% efficiency with an input power of 1.35 kW. A SPT-50 has been laboratory tested down to 0.09 W with an Isp of 700 s and efficiency of 21% (Manzella 1996). At the design point of 0.3 kW, the SPT-50 operated at an Isp of 1160 s and an efficiency of 32%.

The electromagnetic pulsed plasma thruster (PPT) has been in operation on satellites for many years. The concept is relatively simple. A solid (usually teflon) propellant bar is spring loaded inside an insulating container. A capacitor discharge strikes an arc at the propellant surface, vaporizing several molecular layers of the solid and creating a plasma. The same discharge generates an electromagnetic field. This field accelerates the plasma externally, providing a small

thrust pulse. Capacitor discharge frequency is on the order of 1 Hz, with Isp of 1500 s. Typical thrust levels are between 0.05 and 2 mN, which makes this device well suited for accurate spacecraft positioning such as the multi-spacecraft interferometric experiment planned to be launched in 2001. PPTs are possibly the best candidate for many micro-propulsion tasks. The minimum impulse bits obtainable are on the order of 10 μ N-s, with larger impulse bits possible up to 1 mN-s. A total impulse of up to 20 kN-s is targeted for larger systems. Performance does not significantly deteriorate with power level. Total impulse and impulse bit size can be varied by changing the fuel bar geometry.

Characteristics of currently available small thrusters, together with the manufacturer and model, are shown in Table 2. For the Hall thruster, the values given are obtained for a SPT-50 thruster tested at NASA Lewis Research Center. The PPT values are obtained from the specifications of the Deep Space 3 mission.

Table 2. Characteristics of Potential Microthrust Propulsion Systems

	Cold Gas	Solid	Mono-prop	Bi-prop	EHT	Arcjet	PPT	Hall	Ion
Thrust (mN)	4	169000	190	2000	180	150	0.05	5.3	11
Isp (s)	65	270	206	265	304	465	1150	1049	3171
I-bit (mN-s)	0.1	?	2	30			0.06	100	
Power (W)	9		9	18	350	1400	20	90	275
Pow/T (W/mN)	2.25		0.05	0.009	1.95	9.3		16	24.6
Eff. (%)					90	30-35	8	24	62
μ S/C Applic.	Prim./ACS	Prim.	Prim/ACS	No	No	No	Prim/ACS	No	No
Source	Moog 58x125	Thiokol STAR 5A	Primex MR-103C	Aerojet	Primex MR-501	Primex MR-507	Deep Space 3	SPT-50	DERA T5

TECHNOLOGY DIRECTIONS

An important issue that cuts across almost all propulsion systems is the feed system design. The extremely small impulse bits required for a number of secondary functions requires fast valve and regulator response times for propellant feed systems and an overall more compact feed system design. MEMS technology could provide a means to reduce feed system component size. To this end, programs have been initiated to address a number of issues pertaining to valve closing, material compatibility, thermal loads, and bonding of MEMS components to conventional components.

Chemical. A variation of the cold gas systems which has the potential to double the performance is the tri-constituent gas thruster. A non-combustible, stoichiometric mixture of hydrogen, oxygen diluted with a third, inert gas is passed over a catalyst bed, where the H_2/O_2 reaction heats up the third gas, providing approximately double the Isp of cold gas thrusters. The third gas can be nitrogen or helium. For a system which is more volume than mass constraint, xenon could be the third gas because of the higher density Isp. Because of the higher temperatures with Xe as third gas, issues pertaining to catalyst bed and chamber survivability need to be addressed.

Renewed interest in subliming solid thrusters, first investigated in the sixties, has focused mainly on micro-propulsion applications. The high density specific impulse, solid storage, controllability, and capability to produce small impulse bits are all advantages that can be exploited for micro-propulsion. Subliming solid systems can be designed passively by utilization of heat from the spacecraft for sublimation, or actively with heating elements. The last type gives greater controllability, but requires power. For a higher Isp, and to eliminate problems with recondensation of the sublimation products during expansion, heat can be added with a resistive heating element.

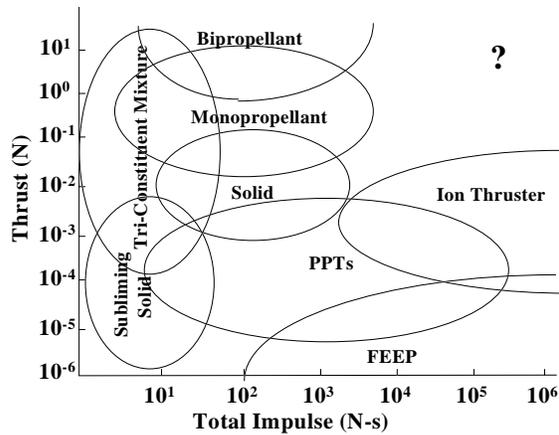
An alternate solid proposed for micro-propulsion is the gas generator compound. A solid compound, usually a compound with high nitrogen content, is stored in solid form. An ignition source, such as laser, pyrotechnic or hot-wire, initiates decomposition. Exothermic decomposition creates a high temperature gas which is accelerated to provide propulsion. No chemical reaction takes place. Proposed uses of a solid gas generator compound is as a solid propulsion device or as a solid storage cold gas system, with the solid compound packaged to replenish the gas in storage.

One potential bipropellant candidate is hydrogen/oxygen propulsion where the propellants are stored until needed in the form of water. Electric energy is used to electrolyze the water into H_2/O_2 , which can be consumed immediately or stored in propellant tanks. A single propellant could be used to provide ACS functions with cold gas accuracy and impulse bits, while the bipropellant combination could be used for high Isp, high thrust level primary propulsion. An additional advantage, described in detail in an accompanying paper (de Groot 1997), is that the same hardware can be used as a fuel cell for energy storage to replace heavy batteries.

Electric. Janson (1994) describes a MEMS fabricated ammonia resistojet. Assuming a 50% thrust efficiency and an Isp of 250 s, the thrust level of this resistojet is 0.41 mN. A proposed application is the orbit raising of sub-kg class spacecraft.

Ion thrusters are the focus of several downsizing programs. Patterson (1997) is developing an 8 cm diameter ion thruster. Estimated thruster characteristics range from an efficiency of about 37% at 1810 seconds specific impulse and 85 W input power, to an efficiency of about 54% at 2960 seconds and 300 W input power. Janson (1994) describes a micromachined ion thruster concept with a projected Isp of 1900 s.

An additional electrostatic propulsion concept is a field emission electric propulsion (FEEP) thruster. Currently being developed by European sources, this thruster concept utilizes liquid indium or cesium as propellant. The expected Isp is over 8000 s with thrust level around 10 μ N. Major technology issues which still needs to be resolved are neutralization of the ions in the plume, feed system difficulties, and spacecraft contamination due to the metallic plume.



Operating Range. A generic graph showing the operating range of the different propulsion systems applicable for microthrust propulsion is provided in Figure 3. The graphs indicated the thrust and total impulse that the different concepts cover, and does not account for the delivery of the total impulse in terms of impulse bits. It is clear that at the high total impulse and high thrust level requirements a void exists that makes a number of missions impossible with current or near future technologies.

Figure 3. Operating Range for Potential Microthrust Concepts.

MEMS Technology. A cross cutting technology that has the potential to aid in the miniaturization of established propulsion systems is MEMS technology and laser lithography. This technology can provide low cost miniature components for feed system valves, orifices, catalyst bed, chamber, nozzle, and heating element. Fabrication details can be significantly smaller than with conventional techniques. When used as a batch manufacturing process, costs of component and systems can be very low.

MEMS technology is an extension of integrated circuit (IC) technology. The base material is silicon. Silicon is an excellent mechanical material, with a strength comparable to steel (Si modulus ~ 190 GPa). However, these excellent mechanical properties start to decrease above $\sim 400^\circ$ C. An alternative base material is silicon carbide SiC, which retains its mechanical properties to well over 800° C. However, MEMS techniques applied to SiC are not as well understood and much harder to implement with the desired details and accuracy than for pure silicon. Common MEMS fabrication techniques are wet and dry bulk silicon etching, used to micro-machine detailed devices such as proposed for micro-thruster development, and surface micromachining, usually employed in the design of sensors. Additional techniques used include bonding, both lower temperature anodic bonding and higher temperature diffusion bonding; micromolding, which utilizes photolithography and electroform deposition to create detailed, three dimensional shapes. Laser lithography, which uses high power, accurate lasers to machine shapes from a silicon substrate is an alternate, non-etching technique.

Many satellite sub-systems can be designed and built with MEMS technology. Miniature sensors, data acquisition, photovoltaic arrays, electronics, fuel cells, and communications antenna can all be designed and build on a single silicon wafer, or on a stack of wafers, with MEMS technology. The development of MEMS-based thruster technology would improve microspacecraft integration issues (Janson 1994). Because of the fact that the current developments in microthruster technology are based on conventional concepts, these MEMS-based microthrusters need to be joined with non-MEMS based propellant storage vessels. The types of joints feasible depend on the storage vessel material and pressure. These issues need to be addressed on a case by case basis.

The transition to MEMS components, specifically MEMS valves, will probably magnify the leakage problems of gaseous storage because of the inability to provide sufficient force on valve

closing and the probability of contaminating the valve seat. MEMS research in the valve area should be directed to mitigate these problems. For the short term, the easiest approach is to perform experiments on concepts that are both easy to execute as well as have some benefit to planned missions. To that end, MEMS based subliming thrusters (Mueller 1997), in which a heating element is used to provide some control over the thrust, MEMS based cold gas thrusters, MEMS based bipropellants, and MEMS based ion thrusters (Janson 1994) are being investigated.

SUMMARY

A number of established propulsion concepts have been analyzed for applicability towards microthrust propulsion. A range of requirements covering the higher thrust levels and higher required total impulse can not be achieved with the current propulsion technology, not even after MEMS technology has been introduced for components. New propulsion technology is needed to enable these missions with microspacecraft.

Candidates for primary propulsion with limited total impulse required are cold gas, solid propellants and monopropellants. PPTs can be used for primary propulsion for selected missions.

Cold gas propulsion is acceptable for ACS functions but can only be applied for very low ΔV missions with limited lifetime. Slew rate requirements can be met with cold gas thrusters. Tri-constituent gas, monopropellants, and PPTs are also candidates for selected ACS micropropulsion tasks. FEEP thrusters can be considered when certain technology issues have been resolved

New developments in fabrication technologies, such as MEMS or photolithography could improve performance of conventional concepts on microscale. Such developments are being tested for cold gas, subliming thrusters, resistojets, bipropellants and ion thrusters.

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REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE March 1998	3. REPORT TYPE AND DATES COVERED Final Contractor Report		
4. TITLE AND SUBTITLE Propulsion Options for Primary Thrust and Attitude Control of Microspacecraft			5. FUNDING NUMBERS WU-910-30-11-00 NAS3-27186	
6. AUTHOR(S) W.A. de Groot				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NYMA, Inc. 2001 Aerospace Parkway Brook Park, Ohio 44142			8. PERFORMING ORGANIZATION REPORT NUMBER E-11132	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-1998-206608	
11. SUPPLEMENTARY NOTES Prepared for the COSPAR Colloquium on Scientific Microsatellites cosponsored by the Committee on Space Research, International Academy of Astronautics, and the National Science Council (NSC), Tainan, Taiwan, ROC, December 14-17, 1997. Project Manager, F.M. Curran, Space Power and On-Board Propulsion Technology Division, NASA Lewis Research Center, organization code 5430, (216) 977-7424.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 70 This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Order of magnitude decreases in the size of scientific satellites and spacecraft could provide concurrent decreases in mission costs because of lower launch and fabrication costs. Although many subsystems are amenable to dramatic size reductions, miniaturization of the propulsion subsystems is not straightforward. There are a range of requirements for both primary and attitude control propulsion, dictated by mission requirements, satellite size, and power restrictions. Many of the established propulsion technologies can not currently be applied to microspacecraft. Because of this, micro-electromechanical systems (MEMS) fabrication technology is being explored as a path for miniaturization.				
14. SUBJECT TERMS Micropropulsion; Microspacecraft; Chemical propulsion; Electric propulsion			15. NUMBER OF PAGES 16	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

