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Performance Trends in Spacecraft Auxiliary Propulsion Systems

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A trade study was conducted to compare the performance of two advanced spacecraft auxiliary propulsion system designs. These are a low-thrust (2-5 lbf) bipropellant system for all on-orbit propulsion functions vs an electrical power augmented hydrazine thruster for north-south stationkeeping in conjunction with a conventional hydrazine system. Both approaches offer a weight savings of approximately 25% over all-catalytic systems for a spacecraft requiring north-south stationkeeping for 7 to 10 years. However, neither system offers any particular performance advantage over the other (i.e., less than 1% difference in total net weight of both configurations). Therefore, system selection criteria must be expanded to include cost, risk, and reliability tradeoffs for upcoming spacecraft missions in the Space Shuttle era. This increased performance issue is of particular importance, because of the potential cost savings associated with reducing the size of auxiliary propulsion systems for spacecraft launched by the Space Shuttle.

Introduction

HOT-gas reaction control systems were first used on operational spacecraft in the early 1960's. These first applications required higher performance, longer life, and higher reliability than the standard cold-gas systems. The two leading candidate monopropellants, hydrogen peroxide (H_2O_2) and hydrazine (N_2H_4), offered significant improvements in these areas.[1] Hydrazine offered advantages of both higher performance and greater stability over peroxide, but suffered from the lack of a spontaneous room-temperature catalyst to initiate the decomposition process. Thus, the first hot-gas systems utilized hydrogen peroxide.[2] Although the decomposition reaction was initiated with an extremely durable and reliable catalyst, peroxide suffered from a fundamental problem of long-term storability. Peroxide will decompose under even the most favorable storage conditions (materials, temperature, etc.). This steady breakdown of the liquid results in a gradual pressure buildup within the storage vessel as well as dilution of the propellant strength (water, a decomposition product, reduces specific impulse).[2] Therefore, spacecraft missions of any length required the use of pressure relief valves in the propellant storage system. These relief valves proved to be unreliable devices, and several spacecraft, including ATS and Syncom, experienced "stuck open" relief valve failures, resulting in a complete loss of system pressure.[3]

These problems, as well as the 30% increase in specific impulse available from hydrazine, made it desirable to switch at the earliest opportunity. This opportunity materialized in the form of Shell-405 spontaneous decomposition catalyst; and the ATS-III (launched in Nov. 1967) and INTELSAT III (Dec. 1968) were the first Earth-orbiting spacecraft to use hydrazine propulsion systems for on-orbit control.[4] Since that time, hydrazine has become so widely accepted that it is used almost exclusively for spacecraft attitude and velocity control propulsion.[5]

At the present time, the next generation of higher performing hot-gas reaction control systems is being developed. These systems offer another increase of approximately 30% in performance over standard catalytic hydrazine systems. Two such systems that are currently being flight qualified are compared in this paper with respect to their potential advantages for spacecraft use.

Need for Higher Performance

Recent emphasis on decreasing spacecraft weight and volume has revitalized interest in achieving higher propulsion system performance. The major impetus for increased performance is based upon the desire to minimize spacecraft launch costs in the Space Transportation System (STS) launch era. Current STS launch cost policy is charted in Fig. 1.[6] Here it is seen that the cost of launching a spacecraft aboard the Shuttle is derived from either liftoff weight or length, whichever is the greater. Reducing the size of the on-orbit propulsion system contributes to decreasing the size of the Shuttle payload.

Current interest in higher performance systems is focused on two approaches. One is the use of an all bipropellant system for complete on-orbit control and the other is the use of a power augmented hydrazine thruster for stationkeeping

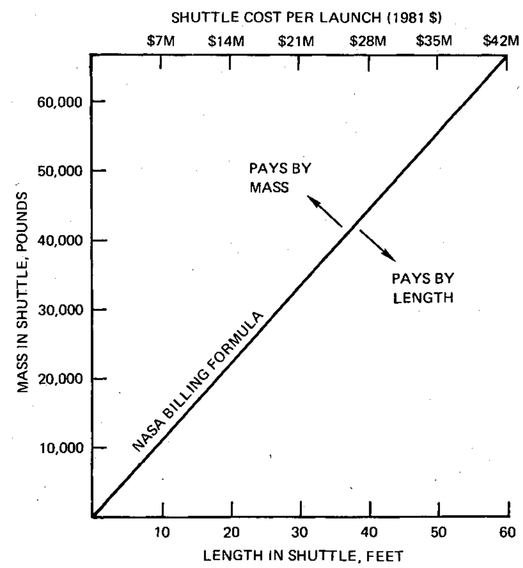

Fig. 1 STS launch costs as a function of launch weight or volume.

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in conjunction with a conventional hydrazine system. Both concepts offer approximate weight savings of 22-35% over a conventional all-catalytic hydrazine system, for a spacecraft requiring north-south (N-S) stationkeeping for 7-10 yr.

Propulsion Subsystem Requirements

Propulsion performance requirements are derived from spacecraft requirements for velocity control (stationkeeping, trajectory correction, and repositioning), mechanization of control authority, pointing accuracy, mission lifetime, launch environments, and the thermal, mechanical, and electrical interfaces.

Propulsion systems are used for on-orbit control of both spin and three-axis stabilized spacecraft and each type has unique requirements. Early geosynchronous spacecraft (1963-1969) had only limited requirements for active stationkeeping propulsion. However, stationkeeping requirements have been increasing for a number of communications (and other) missions in more recent times. Examples of thruster locations and functions for both satellite configurations are shown in Fig. 2.

A major propulsion advantage deriving from spin stabilized control is that the thruster duty cycle is well defined and relatively benign. The total number of pulses required is typically between 20,000 and 100,000 with only a few hundred cold or "thruster ambient temperature" starts being required. However, this is not true for three-axis stabilized vehicles where the duty cycle requirements are usually more severe.

Three-axis controlled vehicles using hot gas for attitude control are relative newcomers to the field of unmanned spacecraft. Very few of these spacecraft use direct "jet control" alone for vehicle stabilization. Some typical examples that do include HEAO and various orbital Agena applications. More typical attitude control mechanizations employ momentum wheels, and rely on gas jets for wheel unloading. Three-axis vehicles generally impose more difficult requirements on the propulsion subsystem because in many cases the exact duty cycle may not be known until the vehicle is flown for the first time. Therefore, only representative duty cycles can be used for thruster development and qualification testing. Typically the attitude control thrusters for three-axis vehicles are required to deliver between 200,000 and a million pulses at very low duty cycles.

On-orbit velocity control requirements are the same as for spinners and are determined by the orbital parameters, payload/mission peculiar needs, and the life of the satellite.

Propulsion System Flight Application Summary

The first hot-gas applications for communication satellites occurred in the 1963-1965 time frame with Syncom and Earlybird (INTELSAT I). These applications are grouped by time frame and specific impulse capability in Fig. 3. It is seen from this figure that flight qualification of the high-performance electrically augmented hydrazine thruster and/or the bipropellant orbit control system will result in essentially double the performance achievable with peroxide in the 1960's and improve the results achievable with conventional hydrazine by about 30%.

A description of the typical and unique design features of these advanced hardware systems, along with the results of performance and reliability/risk tradeoffs and issues are presented next.

System Designs Under Development

The generation of spacecraft on-orbit propulsion systems currently under development is comprised of two diverse concepts. The monopropellant system being developed is an upgrading of standard hydrazine systems that have been in use over the past 15 years. This upgrading consists of the use of high performance or "augmented" thrusters for the high ΔV requirements of N-S stationkeeping.[7] The bipropellant systems are lower thrust versions of the relatively standard N_2O_4/MMH propellant systems used for the majority of expendable launch vehicles, as well as the Space Shuttle orbiter itself. This section describes these systems and points out their capabilities as well as constraints.

A typical hydrazine propulsion system utilizing high-performance electrothermal hydrazine thrusters (HiPEHT) is shown schematically in Fig. 4.

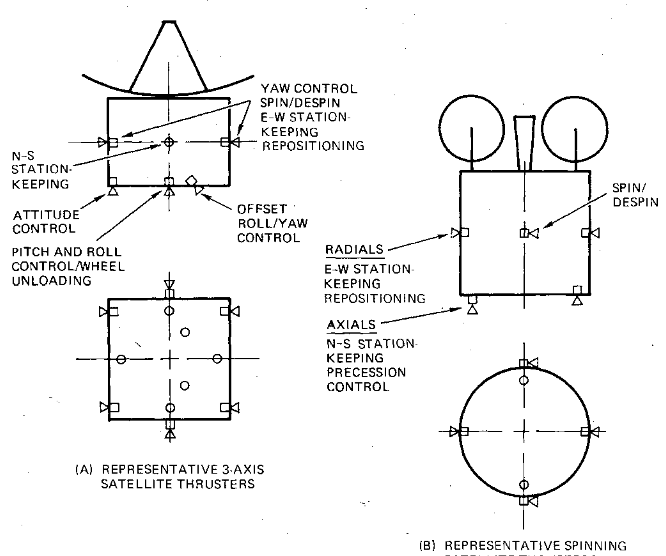

Fig. 2 Representative thruster locations and functions for three-axis- and spin-stabilized satellites.

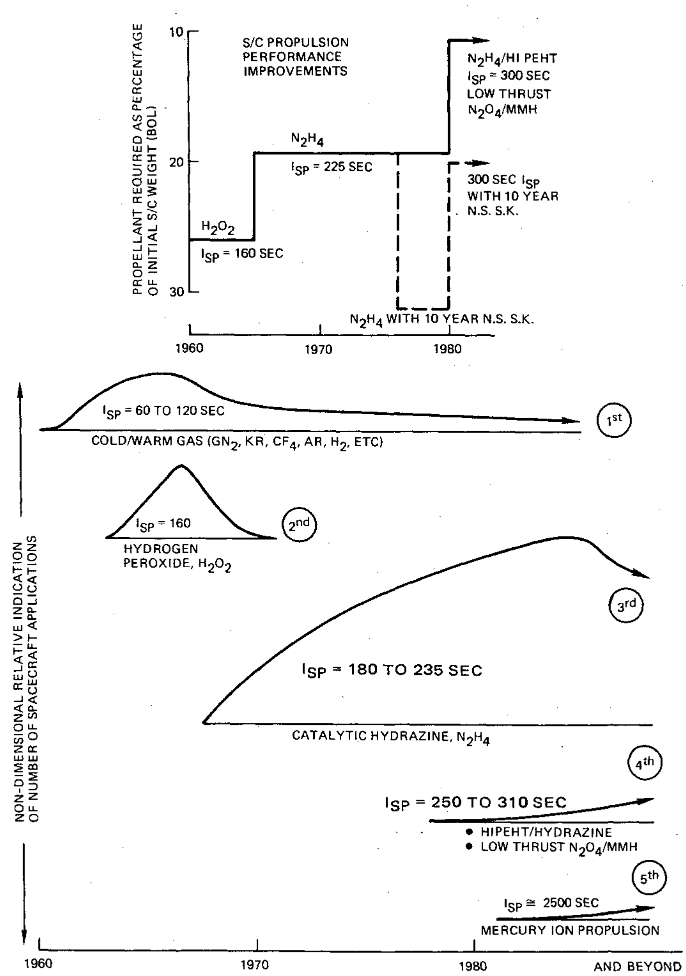

Fig. 3 Generations of spacecraft on-orbit control propulsion system applications.

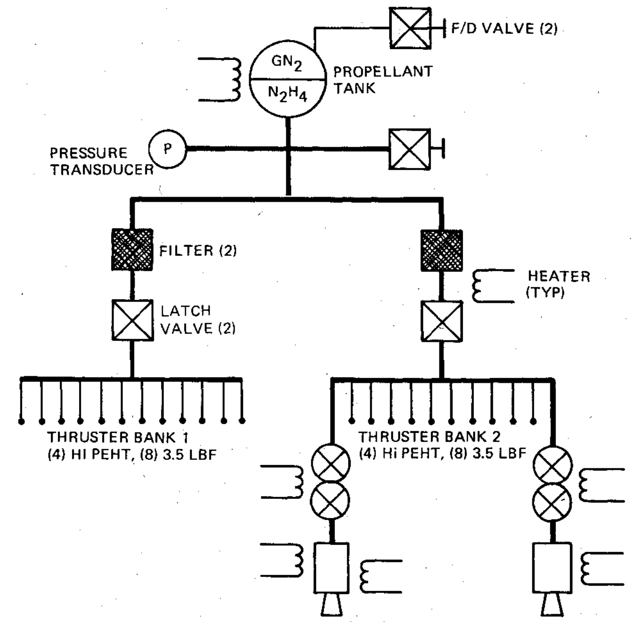

Fig. 4 Baseline schematic diagram—monopropellant system.

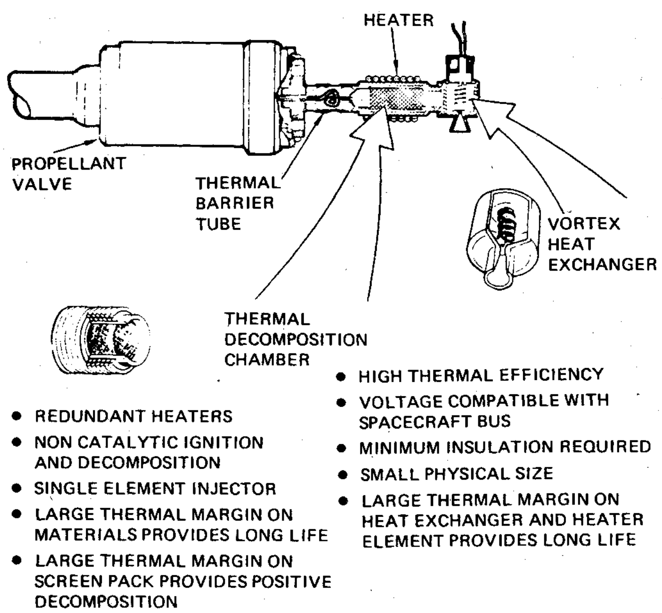

Fig. 5 HiPEHT design features.

The major driver for the development of these thrusters is the approximately 28% specific impulse increase over standard catalytic thrusters (~300 vs 235 s). This increase can save up to 80 lb of propellant which could lengthen the life in orbit by 2-3 yr. The high performance is obtained by electrically augmenting the enthalpy of the decomposition products of hydrazine in a second-stage vortex chamber as shown in Fig. 5.[7] The HiPEHT thruster is presently being developed for use on the INTELSAT V spacecraft. The HiPEHT qualification tests are scheduled to be complete by the last quarter of 1980. Development units to date have demonstrated 215 h of operation, 185 lbm of propellant throughput, and >300 s of specific impulse (I_{sp}).

The second advanced system concept is a low-thrust liquid bipropellant configuration, as shown in Fig. 6. A bipropellant system such as this, for on-orbit attitude and velocity control, is planned for the INSAT communication satellite.[8] This is the first known U.S.-built application of a bipropellant system for a 10-yr mission life satellite that performs both

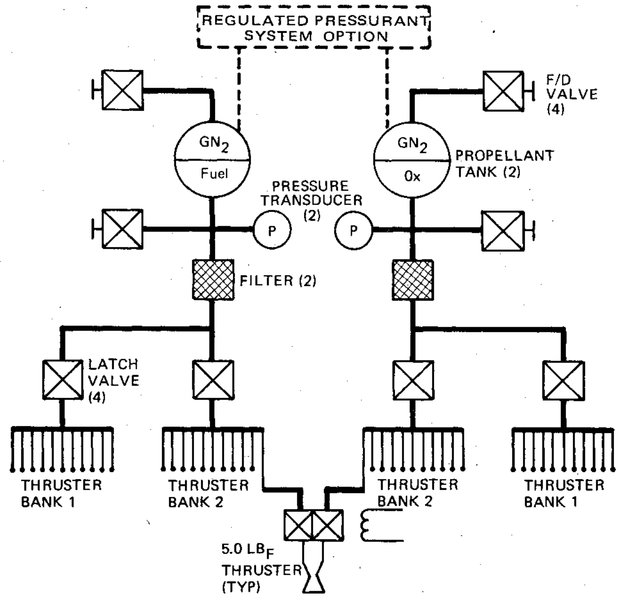

Fig. 6 Baseline schematic diagram—bipropellant system.

apogee orbit insertion (100 lbf thrust) and on-orbit control (5 lbf thrust). A similar system is currently flying on the Symphonie satellite which supplies on-orbit velocity control (ΔV) impulse.[9] While most low-thrust bipropellant engine performance data have been generated at the 2.5-5.0 lbf thrust level (low-thrust bipropellant engines are currently being produced), development work has recently been initiated on a 0.5 lbf thruster. The final development phase is presently in progress.

The major driver for the use of bipropellant systems is also higher performance (300-310 s) and the ability to combine the on-orbit ACS function with the orbit insertion propellant tankage, which may lead to more efficient system packaging because of common tankage and components.

Hardware Development/Flight Status

Table 1 summarizes the known usage and characteristics of HiPEHT/hydrazine and bipropellant systems presently in orbit or under contract for upcoming satellite applications. Available tank data were included in this table since the choice of available bipropellant tankage is somewhat limited. Because of this limited data base, little or no operational performance and compatibility data exist for bipropellant propulsion systems used for attitude and velocity control of spacecraft on-orbit. This lack of component and system data raises a number of concerns for the reliability of bipropellant systems for typical missions which require 10 yr lifetimes and a variety of thruster operating modes. These concerns are discussed in the next two sections.

System Tradeoff Study Results

A tradeoff study was performed to compare the propellant and system dry weights of three candidate on-orbit propulsion systems described in this paper; i.e., conventional catalytic hydrazine, hydrazine system with HiPEHT for N-S stationkeeping and catalytic thrusters for all other functions, and N_2O_4/MMH bipropellant system.

The baseline spacecraft configuration and mission requirements for the tradeoff were assumed to be typical of a three-axis-controlled geosynchronous satellite incorporating momentum wheels for on-orbit attitude control. A representative thruster duty cycle was generated to calculate mission impulse and thruster I_{sp}. This duty cycle and other tradeoff assumptions (strawman system requirements) are shown in Table 2. Using bipropellant data for 5.0 lbf nominal thrust engines and hydrazine thruster performance measured

Table 1 On-orbit attitude control high-performance system hardware status

		System characteristics							
		Tankage							
System	Status	No.	Expulsion device	Size	Propellant capacity	Pressurization system	Thrust level, lbf	No. of thrusters	Mission life
Bipropellant									
Symphonie	Flown	4	Bellows	Data not available	67 lb	Blowdown 360-180 psi	2.25	7 (banks of 3 and 4)	Launched Dec. 1974
Galileo	In development	4	Spin	28 in. diam sphere	Combined with apogee system	Regulated 260 psi	2.25	14 (two banks of 7)	5 yr
INSAT	In development	2	Surface tension	33 in. diam sphere	1279 lb total combined with apogee system ≈ 192 lb for ATC	Blowdown 200-180 psi	5.0	12 (two banks of 6)	10 yr
HiPEHT/Hydrazine									
INTELSAT V	In development	2	Surface tension	18 in. diam 38 in. long	460 lb (max)	Blowdown 350-110 psi	5.0 0.6 0.1	20 (two banks of 10)	10 yr

Table 2 Straw-man requirements for baseline duty cycle and trade assumptions[a]

	Thruster percent duty cycle		Maneuver requirements	
Mission phase	ΔV thrusters	AC thruster	ΔV	AC impulse, lb-s
Repositioning	95-100	4-7	31 ft/s	83
E-WΔV	85-100	4-9	67 ft/s	1183
N-SΔV	85-100	0.06-8	1590 ft/s	4930 (bipropellant) 8034 (HiPEHT)
On-orbit normal mode	N/A	Bed ambient pulses	N/A	1189

[a] Baseline assumptions: BOL S/C weight = 2818 lb; E-W thruster cant = 10 deg; N-S thruster cant = 6.6 deg; N-S thruster plume drag loss (solar array) = 11.6% average; HiPEHT cannot be off-modulated, requires AC thruster firing during N-SΔV; bipropellant can be off-modulated during ΔV; HiPEHT thrust range = 0.100-0.040 lbf; bipropellant thruster range = 3.5-1.5 lbf, 10 Ms pulse width; catalytic thruster range = 1.0-0.4 lbf, 50 Ms pulse width.

during engine prequalification and acceptance test programs, system propellant weights were calculated for the Table 2 requirements. The resulting propellant weights for the three candidate systems are summarized in Table 3.

Both the bipropellant and HiPEHT systems offer approximately 22% propellant savings over the conventional catalytic hydrazine system. The propellant difference, however, between these two high-performance systems is less than 1% under the assumptions used for this tradeoff.

The total system weights (dry plus propellant) for the bipropellant and HiPEHT systems are shown in Table 4. Dry weights were estimated for: blowdown feed system using qualified tankage, full functional redundancy with isolation capability typical of the schematics shown in Figs. 4 and 6, 20 bipropellant thrusters, 16 catalytic thrusters plus 8 HiPEHT units, and separate bipropellant system (not shared with an apogee boost system).

Again, there is less than 1% difference in the total subsystem weights. The selection of either system for flight applications is, therefore, dependent on a risk, cost, reliability and technology assessment of the hardware, and flight experience (and associated confidence) of the systems.

Areas that must be examined and compared in the final selection process are: 1) operational experience with both approaches; 2) system compatibility including: propellant storage, plume interaction with spacecraft materials, and thruster material compatability; 3) risk including: qualification/development status, untested operational modes, and flight data; 4) cost/producibility; 5) reliability (i.e., quantitative assessment); 6) spacecraft interface and interactions including: electrical/power availability, attitude control (thrust level, duty cycle limitations, repeatability,

Table 3 System propellant weight comparison (all weights in lb.)

Maneuver	Conventional hydrazine	Hydrazine with HiPEHT	Bipropellant
Reposition			
ΔV	12.5	12.5	10.1
AC	0.5	0.5	0.4
E-W stationkeeping			
ΔV	26.8	26.8	21.7
AC	6.8	6.8	5.2
N-S stationkeeping			
ΔV	652.3	479.8	518.7
AC	30.8	45.9	21.7
On-orbit AC	9.9	9.9	6.5
	739.6	582.2	584.3

Table 4 Total system weight comparison (lb)

System	Propellant weight	System dry weight[a]	Total weight
Hydrazine with HiPEHT	582	108	698
Bipropellant	584	103	687

[a] Propulsion system dry weight only; assumes power is available for operation of HiPEHT without additional solar array.

Table 5 High-performance system technology concerns

Concern	System status: Bipropellant	System status: HiPEHT/Hydrazine
Material compatibility	Limited long-term on-orbit data with continuous thruster usage.[a] Susceptible to oxidizer reopexy Symphonie plugging history (presumably caused by contamination due to improper cleaning/handling).	Hydrazine storage and material compatibility for long life demonstrated on numerous S/C Thruster/high-power heater operation at elevated temperatures (>3000°F). Ammonia/aniline poisoning of catalyst beds.
Plume contamination	Oxidizer or fuel-rich (mixture sensitivity) exhaust effects on S/C surface properties needs to be examined in more depth.	Extensive test and analysis performed for N_2H_4. Extensive flight experience with exhaust products.
Thruster operation	Limited duty cycle demonstrated at thrust levels ~ 5 lbf. Potential thermal/performance operational constraints may be identified. Thrust levels lower than 2.5 lbf not qualified.	Catalytic thrusters well-characterized; no operating mode limitations on most low thrust (~5 lbf) engines with catalyst bed heaters. Thrust levels down to 0.020 lbf available. HiPEHT not qualified for off-modulation. Alternate configuration designs being evaluated for modulation duty cycles. Higher thrust levels require more power.
NVR buildup	NVR characteristics will be demonstrated in upcoming thruster qualification programs.	Throughput/life limitation for thrusters with feed tube diameters ≤0.010 in.
Attitude control interactions	Thrust levels ≤1.0 lbf desirable for attitude control optimization. Present thruster being qualified are 2-5 lbf class.	Wide range of catalytic engine thrust levels (≥0.1 lbf) flight qualified available for optimized ACS. HiPEHT thrust level <0.1 lbf.

[a] Data exists for storage of bipropellants for periods of up to 8 yr on such programs as Titan (silo storage), Viking (on-orbit) and Mariner 71 (on-orbit). However, this data bank relates to static storage (few and infrequent engine firings) and operation of relatively high thrust (>100 lbf) engines. Very little or no data exists for low-thrust bipropellant engines operating frequently over long periods in orbit.

etc.), and thermal; and 7) need for bipropellant apogee system (potential tankage and component sharing with on-orbit system).

Risk Trades and Reliability Concerns

Both high-performance propulsion systems (HiPEHT/hydrazine and bipropellant) are presently being qualified for spacecraft scheduled for launch and operation within the next few years. There are a number of concerns with each of these systems for typical missions requiring 10 yr life due to lack of long-term on-orbit operational data and experience. These concerns are summarized and compared in Table 5 and discussed in detail in the following paragraphs.

Long-Term Compatibility

Long-term orbit operation data for low-thrust bipropellant systems are limited. It has been demonstrated that oxidizer (N_2O_4) reopexy can lead to gel formation[10] which can occur during oxidizer flow through fine mesh filters and small flow passageways, dependent upon material compatibility and prior hardware cleaning. Although proper cleaning procedures minimize the possibility of N_2O_4 gel formation, the effect of long-term storage and operational temperature excursions of system hardware are not well characterized. The first Symphonie propulsion system has experienced total plugging of some thrusters in the first year of operation.[11] This may have been related to N_2O_4 gel formation or could be the result of inadequate system cleaning as reported in Ref 11.

NVR Buildup

Buildup of nonvolatile residue (NVR) from propellant in small-diameter propellant feed tubes (diam ≤ 0.010 in.) seems to limit the maximum impulse capability of the HiPEHT thruster.[12] A similar problem with bipropellant thrusters may occur since heat flux, passageway diameters, and propellant cleanliness are similar to hydrazine thrusters.

Attitude Control Requirements

The lowest thrust bipropellant engines currently being qualified/flown are in the 2.5-5.0 lbf thrust range. Lower thrust engines are sometimes preferred for attitude control requirements for fine pointing, impulse repeatability (longer valve on-times for the required impulse bit results in improved valve and thruster performance levels and repeatability), and spacecraft dynamic response (bending stability). High-thrust engines ultimately require more propellant usage because of higher control torques (produced by a combination of high thrust and moment arms for thruster locations) and associated spacecraft rates.

The HiPEHT thruster has not been qualified for off-modulation mode operation in the current configuration because of limitations in the life of the current augmentation heater design. This requires that any thrust mismatch between two thrusters fired simultaneously be corrected with on-board catalytic thrusters with a resultant penalty in propellant utilization. This is reflected in the attitude control propellant requirement for HiPEHT in Table 3.

Thruster Operation

Qualification of low-thrust bipropellant engines for limited duty cycles is presently being performed in the industry. INSAT requires operation over a very shallow blowdown range (200-160 psi). While the goal is to demonstrate operation over blowdown ranges of 3:1, problems are anticipated for this pressure range typically required for the low cost/weight blowdown tankage systems. If regulated systems are required due to thruster constraints, the propellant supply system complexity and cost may increase dramatically.

Operational limitations (duty cycle constraints) may be encountered because of thermal or mixture ratio limits. This type of problem has been troublesome for hydrazine thrusters, and years of testing and analyses were required to develop thrusters that were not duty cycle limited. For bipropellant engines, the problem is more severe due to mixture ratio variations with duty cycle and inlet pressure range, heat flux/cooling requirements for the injector head-end, and propellant temperature sensitivity on performance. Three-axis-controlled spacecraft require a wide range of duty cycles that are difficult to completely define by analysis; therefore, an unlimited duty cycle capability is required.

Conclusions

Various hot-gas reaction control systems have been used for the orbital control of satellites for about 15 yr and have performed well through several design generations. With the emergence of monopropellant hydrazine as the pre-eminent orbital control propulsion medium, flight applications of hot-gas systems increased by an order of magnitude. Extremely reliable performance has justified this confidence. In fact, this increased reliability has caused longer life requirements and step jumps in incremental velocity requirements so that orbit control propulsion system weight has come to exceed 20% of the total satellite (beginning-of-life) weight. In fact, in two recent applications, i.e., TDRSS/Advanced WESTAR (where propellant weight is 35% of the total) and INTELSAT IV-A,[2] propulsion is the heaviest subsystem onboard, weighing even more than the payload (communications subsystem). Therefore, in the STS launch era, where weight and volume can affect launch costs significantly, high premiums are being placed on propellant savings, through increased specific impulse.

Both bipropellant and electrothermally augmented hydrazine thrusters are being developed for this purpose with flight qualification of both technologies expected in the near future. Both will result in about 22-28% reduction in the propellant requirements for a 10-yr mission with north-south stationkeeping, when compared with a conventional catalytic hydrazine system. However, there is less than 1.0% difference in the total wet weight of typical configurations of these systems relative to each other.

The key point is that the choice of propulsion weight savings technology should be based upon cost, risk, and reliability criteria from a total system point of view. It may well be that both propulsion technologies are required, depending upon particular satellite mission requirements. In any event, it appears almost certain that the first phase of the next generation of spacecraft propulsion subsystems will utilize both low-thrust bipropellant and power-augmented hydrazine thruster systems.

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