combining both equations the resulting differential equation is

$$p_{xx}' - a^{-2}[p_{tt}' + 2\pi\nu\phi p_t'] = 0 \tag{6}$$

where

$$\phi = [(\bar{M}^2 - 1)aA_x]/[\bar{M}2\pi\nu A] \tag{7}$$

and

$$\bar{M} = \bar{u}/a$$

It may be noted that in a supersonic nozzle in which there is a supersonic flow in the divergent section, $\phi(x)$ is always $\geqslant 0$. For $\phi = 0$, which is true for a constant cross-section tube, $A_x = 0$, and Eq. (6) is reduced into a one-dimensional wave equation with a solution $p' = P\exp[j2\pi\nu\{(x/a) - t\}]$, where P is the amplitude of the pressure fluctuation. We seek now a similar trial solution such that, when substituted in Eq. (6), it will satisfy the solution for $A_x = 0$ also. Since the sound speed in the nozzle is not constant, the trial equation for p' considered is

$$p' = P\exp\left[j2\pi\nu\left\{\int a^{-1}dx - \int(1+\lambda)dt\right\}\right] \tag{8}$$

In Eq. (8), λ is complex, in which the real part gives the change in the frequency and the imaginary part gives amplification or damping of the amplitude of pressure fluctuation at a reference point $x = 0$.

Substituting Eq. (8) into Eq. (7), one gets a quadratic equation and a solution for λ is given by the relation

$$\lambda = -1 + 0.5j\phi + (1 - 0.25\phi^2)^{0.5} \tag{9}$$

Real and imaginary parts of λ depend on the value of ϕ, and are given by the following relations

$$\phi \leqslant 2{:}\,\mathrm{Real}(\lambda) = -1 + (1 - 0.25\phi^2)^{0.5}, \quad \mathrm{Im}(\lambda) = 0.5$$
$$\phi > 2{:}\,\mathrm{Real}(\lambda) = -1, \quad \mathrm{Im}(\lambda) = 0.5 \pm [(\phi^2/4 - 1]^{0.5} \tag{10}$$

Conclusions

It may be pointed out from Eq. (10) that for all possible positive values of ϕ, Real(λ) is always negative and Im(λ) is always positive. Therefore, along the nozzle the frequency is always reduced and amplitude is always damped. Furthermore, ϕ is large or small depending on whether the frequency of fluctuation is small or large. However, it is not clear at the moment which of the two solutions for damping of the amplitude of the pressure fluctuation is valid for low frequency oscillations.

From the calculated distribution of λ along the nozzle for a given frequency, it is possible to obtain the extent in which the frequency and amplitude vary along the nozzle. This can then be used with the help of Eq. (5) to obtain the amplitudes of fluctuations of other flow variables.

At this point it can only be speculated whether the method is applicable also in understanding the jet noise in the supersonic portion of a supersonic jet. Following Powell,[5] who made his comments about fluctuating pressure (shock) fronts for underexpanded supersonic jets only, it may be conjectured that sound emanating from the supersonic part of the jet of a well-expanded nozzle will depend on the fluctuating pressure fronts on the surface of a region at which $\bar{M} = 1$. In other words, the investigation can be carried out to find pressure fluctuations in a one-dimensional convergent nozzle of the same size as that of the supersonic region of the supersonic jet. For such a case as the preceding analysis $\phi(x) \leqslant 0$, and, thus, the amplitude of pressure fluctuation is continuously increasing after emanating from the jet exit. As a result it is expected that intensity of sound emanating from the supersonic region will be increasing along the flow, a fact known from experiments.[4]

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One-mlb Colloid Thruster System Development

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Introduction

Low thrust secondary propulsion systems (SPS) using electrostatic propulsion techniques are desirable on geosynchronous satellites requiring extremely close pointing accuracy or tight stationkeeping.[1,2] SPS requirements for initial station aquisition, repositioning, attitude control, and stationkeeping are discussed in Ref. 3. Geosynchronous mission requirements for the colloid SPS, as well as its ability to meet these requirements, are described in Ref. 4. The colloid SPS is particularly well suited for performing the stationkeeping function.

System Description

Currently, the colloid SPS is in advanced development.[5] The development program goals include flight qualification of a radiation-hardened system that delivers 4.4-mn (1-mlb) thrust at 1500-sec specific impulse (I_{sp}) and 70-w input power. The critical components for this system have been developed and tested together in breadboard fashion.[6,7] These components consist of a 432-needle thruster, a thermionic tungsten filament neutralizer assembly, a positive expulsion bellows propellant feed system, and an inductor energy storage power conditioning and control system (PCCS). During breadboard system testing, the thruster, neutralizer assembly, and feed system are mounted on a thrust stand inside a vacuum test facility. The PCCS is operated in air, and connects to the components mounted on the thrust stand by means of vacuum feedthroughs on the test chamber.

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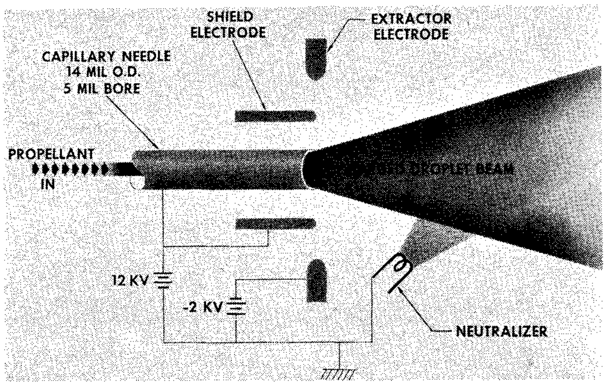

Fig. 1 Thruster needle source.

The thruster employs conventional 0.36-mm (14-mil) o.d., 0.13-mm (5-mil) bore needle sources with NaI-doped glycerol propellant.[8,9] A 0.16-cm ($\frac{1}{16}$-in.) o.d. shield electrode surrounds each needle as shown in Fig. 1. The needle and shield are concentrically positioned within a 0.32-cm ($\frac{1}{8}$-in.) extractor electrode aperture. The needle and shield are nominally operated at 12 kv, and the extractor at -2 kv. The shield electrode permits the needle source to operate at higher voltage, and consequently, higher specific impulse than before without degrading other performance factors. Using a shield electrode also confines the exhaust spray to a smaller angle and prevents electrons from the extractor from bombarding the critical rim area of the needle. Such bombardment can cause propellant decomposition, polymerization, and life-limiting material build-up at the needle rim.

The 432-needle thruster is assembled from a dozen modules, each with 36 positive-voltage needle sources and an individual extractor electrode. The modules are located four on a side of a square array. A heater bonded to the back of the array frame provides active thruster temperature control. The center of the array is left open for access to a propellant manifold that couples modules to a propellant flow controller assembly.

The system components are physically separated into two packages: the thruster unit, and the PCCS. Figure 2 shows the thruster unit comprised of the thruster, neutralizers, and propellant feed system. Two neutralizers are used, one for redundancy. The PCCS is contained in a separate electronics enclosure. It converts 28-v d.c. spacecraft input power to the regulated power levels and forms required for thruster unit operation. The thruster unit and PCCS are tied together electrically.

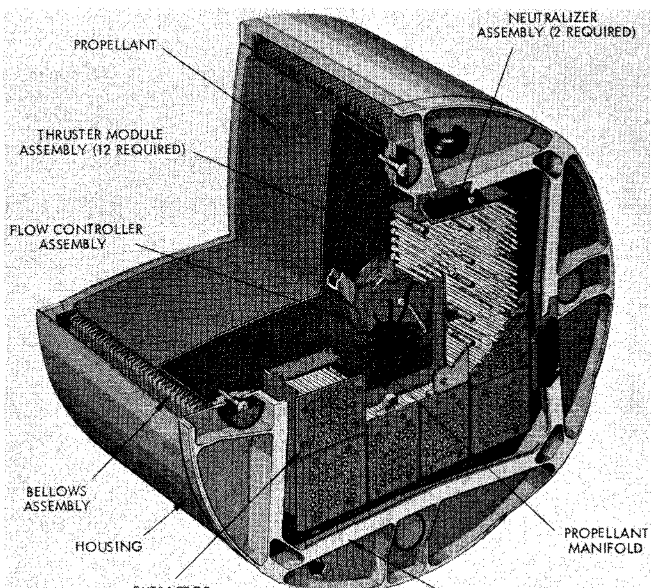

Fig. 2 The 432 needle thruster unit.

The total projected system weight is 21.8 kg (48 lb). Fully loaded, it includes 11.4 kg (25 lb) of propellant. At 95% expulsion efficiency[5] and 1500-sec I_{sp}, a total impulse capability of 158,000 nsec (35,600 lb-sec) is provided. The total weight includes 1.4 kg (3.0 lb) for the thruster, 0.05 (0.1) for the neutralizers, 3.1 (6.8) for the feed system and 3.6 (7.9) for the PCCS.

The projected system power of 68 w is based on 70% thruster efficiency for a beam power of 47 w. It also includes 5 w for the neutralizer, 2 w for the thruster heater, and 2 w for the propellant flow controller. A 12.5-w PCCS loss was measured with the breadboard electronics operating under full load at nominal input voltage. The over-all PCCS efficiency was 81%. The high voltage converter itself had a measured efficiency of 90%.[10]

Thruster Performance

Time-of-flight data taken with a 36-needle thruster module have exhibited 1550-sec I_{sp} and 75% efficiency at rated thrust. These results, however, are very sensitive to the cleanliness of the thruster itself. They are markedly affected by the presence of pump oils in the test environment that affect propellant wetting at the needle tips. Variations in source geometry because of manufacturing procedures have also been found to influence performance. A thorough understanding of the influence of the test environment and source geometry tolerances on thruster performance is required to reproducibly achieve design goals.

Table 1 compares 432-needle thruster design goals with typical performance data and the best data obtained on a thrust stand during breadboard system testing. Typical thruster performance data as a function of mass flow are shown in Fig. 3. The thrust and needle current curves were used to calculate specific impulse and efficiency that are also shown. These data were taken during a breadboard system life test that was voluntarily terminated after more than 1000-hr operation (the test lasted for 1117 continuous operating hours, all but 100 of which were with the valve open and mass flow greater than 280 μg/sec).

A module life test accumulated over 3000-hr operation at 12.3-kv needle voltage, 25-μg/sec mass flow, and 25°C. Average time-of-flight module performance from the test exhibited 0.33-mn (75-μlb) thrust, 1350-sec I_{sp}, and 69% thruster efficiency. The most noticeable change was a gradual decrease in average charge-to-mass ratio with time from 12.5 to 10.0 coul/g with corresponding declines in needle current, thrust, and specific impulse. Efficiency remained fairly constant. For example, over a 2200-hr period, needle current dropped from 310 to 250 μa, thrust dropped from 0.36 (80) to 0.33 mn (74 μlb), and I_{sp} dropped from 1450 to 1320 sec.

Table 1 Thruster performance

	Design	Typical	Best data
Thrust, mn (mlb)	4.4 (1.0)	4.4 (1.0)	4.6 (1.05)
Specific impulse, sec	1500	1180	1540
Thruster efficiency, %	70	53	72
Needle voltage, kv	12.3	12.8	12.7
Needle current, ma	3.8	3.8	3.7
Beam power, w	46.7	48.6	47.0
Mass flow rate, μg/sec	303	390	310
Average charge-to-mass ratio, coul/g	12.5	10.3	11.9

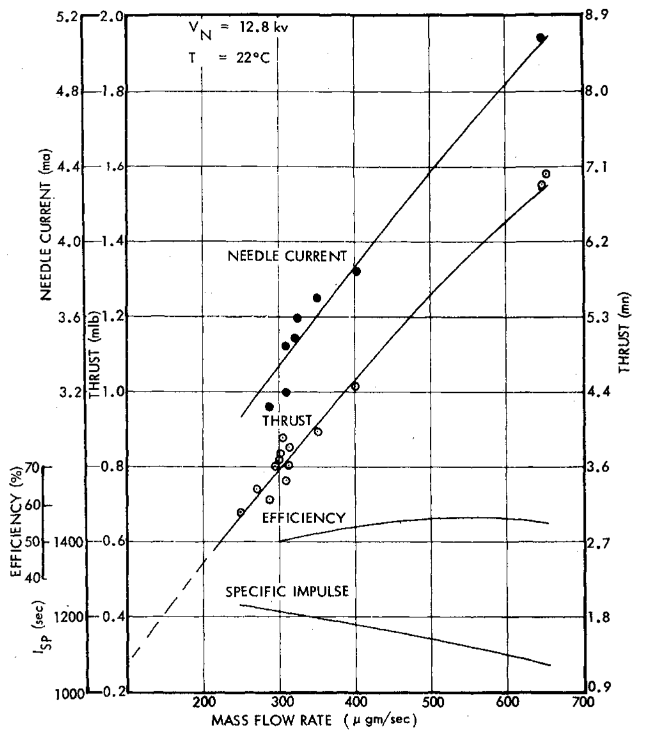

Fig. 3 Thruster performance vs mass flow (constant needle voltage and thruster temperature).

Other Component Data

Five neutralizers were subjected to accelerated life tests.[7] The neutralizer filament is a 6.3-cm (2.5-in.) length of 0.053-mm (2.1-mil) diam bare tungsten wire. The tests showed that an 8.5% reduction in filament diameter will occur after 24,000 hr. At this point the filament temperature profile remained uniform. Actual burn-out was not observed until a 12% reduction in diameter had taken place. Operation beyond 24,000 hr, however, will be unsatisfactory because of nonuniform electron emission that required increased injection potential.

The propellant feed system has shown satisfactory characteristics in component tests. In system integration tests, however, propellant tension has not been maintained in the volume between the propellant flow controller valve seat and the thruster needle tips when the valve is closed. It is believed that a gas bubble was trapped during initial propellant filling of this volume. As a consequence, system start-up and shutdown remain to be evaluated. PCCS performance data have previously been reported in Ref. 10.

Conclusion

Difficulties have been encountered in attempting to reproducibly demonstrate design level performance in ground test facilities. The results (Table 1) are influenced by the wetting characteristics of the needle tips in the test environment.

Life test results to date have been encouraging. A module has operated for over 3000 hr at 69% thruster efficiency and about 1350-sec I_{sp}. The breadboard thruster system was operated over 1000 hr. Accelerated neutralizer life tests in a separate vacuum bell jar indicated 24,000 hr of filament life.

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Material Evaluation under Direct Rocket Exhaust Impingement

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Introduction

THE multiple independent re-entry vehicle (MIRV) capability was added to the Minuteman weapon system effective with the Minuteman III model. A major change required was the addition of a post boost propulsion system (PBPS) to add velocity and positional adjustments to the final stage for each re-entry vehicle deployment. Bell Aerospace Co. developed the PBPS under subcontract to North American Rockwell Autonetics Div.

The Post-Boost-Propulsion System is housed in the aft 18 in. of the 52 in. diam fourth stage. Final staging is effected by a circumferential separation ordnance ring at the aft plane of the fourth stage. Activation of the separation ring is followed by third stage retrothrust which is achieved by opening six uniformly spaced ports to the third stage combustion chamber. Exhaust from each port is ducted forward at a 45° angle forming a conical expanding flow around the fourth stage. The third stage retrothrust does not pass through the third stage c.g. and as the stages separate third stage pitch/yaw rotation sweeps the retrothrust gases across the aft surface of the fourth stage.

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