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High-Thrust Density Colloid Source Development

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An improved high-thrust colloid emitting source is being developed as the basic microthruster for use in 0.1-1 mlb (0.5-5 μN) electric thruster systems in the 1000–2000 sec specific impulse range. The source, a thick needle type geometry, is shown to be a result of work with earlier linear and annular slit geometries. Short and long term performance, including a 2000-hr continuous life test, is discussed. Electrostatic thrust vectoring performance characteristics and reliability implications are also discussed.

Introduction

ALTHOUGH colloid microthruster systems are already competitive as secondary propulsion systems for certain missions on Earth orbiting spacecraft,[1] further increases in thrust density can lead to additional size and weight savings. A research program is currently underway with the objective of attaining improvements over the performance of conventional needle type colloid thrusters. Specific advantages sought are 1) high-thrust density leading to a minimum thruster size and weight, 2) fewer number of individual components per thruster, and 3) the development of a two-dimensional electrostatic thrust vectoring capability.

Thruster Development

The search for a high-thrust density colloid source began at TRW with three independent lines of investigation: a) the thick needle concept was originated in 1965 and was investigated until late 1967 when 0.028″ OD needles were tested,[2] b) the linear slit geometry research dates back to mid-1964 and was the subject of extensive investigation over the 1966–68 period,[3] and c) annular slit geometry research was begun in early 1965 and work has continued to the present time by several researchers.[2,5]

The linear slit geometry requires higher voltages than conventional needle geometries to produce a given extraction field. Thus, a higher I_{sp} is attained for a given charge to mass ratio. In addition, the linear source is a geometrically continuous emitter, resulting in high-thrust density. Scalability of this concept was demonstrated by developing a module[4] consisting of two parallel slits, each having an emitting length of 1.5 cm. The module produced 220 μN thrust at 1500 sec specific impulse. Excessive fabrication difficulties, wide beam spread and limited thrust density have discouraged further development of this concept.

Small diameter double rimmed annular slits have also been investigated. These have been shown to have better focussing properties than linear slits, but field enhancement at the smaller diameter inner extractor has caused voltage breakdown problems. Increasing the source diameter can eliminate this problem. However, this results in a return to the basic performance features of the linear slit geometry since its radial field divergence is now less significant in the vicinity of the emitting rim.

A cure for the central extractor voltage breakdown problem would be to eliminate the center extractor. One such configuration[4,6] consists of a small diameter annular slit in which the inner emitting rim and extractor are replaced by a central plug, held at source potential. Recently, devices of this type have achieved 110–180 μN of thrust at 1500 sec I_{sp} with high-beam distribution efficiency and low-beam spread. In addition to single unit tests, multisource module experiments have also been performed. A seven unit module has been life tested for 500 hrs. Tests such as these indicated that the life limiting factor for these devices was performance degradation due to sediment buildup on the center plug. This problem was then solved by eliminating the center plug, thus letting the center fill with sufficient fluid to maintain a liquid solution. In the following, we discuss the performance of this latter device.

Thruster Design

Figure 1 shows the major design details of the thruster. The main features of the emitter are a sharp radius of curvature ($\simeq$0.025 mm) and an experimentally designed "meniscus

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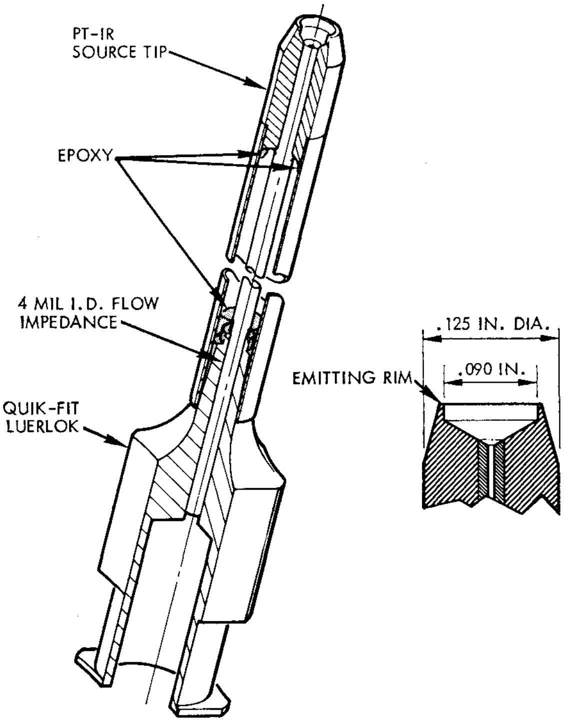

Fig. 1 Schematic of TRW high-thrust source geometry.

well," holding a minimum of exposed propellant to give an optimum meniscus shape.

A separate, small bore tube is brazed into the structure to provide the proper propellant inlet impedance. In order to provide stable, long term operation, the emitting rim is made from platinum-iridium, which has been determined from previous single needle research at TRW to provide the necessary corrosion and erosion resistance needed for long term operation. Vectoring is provided by three closely spaced cylindrical electrodes as shown in Fig. 2. The entire structure fits in a 0.25-in. diam extractor hole. The beam can be vectored through a small angle in any direction by applying the proper combination of vector potentials. The vector electrodes are manufactured from sections of stainless steel tubing which are brazed into an underlying support structure.

Experimental Station

The thruster was tested in a 4 ft diam by 8 ft long horizontal vacuum facility. A 10-in. diffusion pump and a liquid nitrogen cooled shroud provided background pressures of the order 2×10^{-6} torr during normal operation. A deflector voltage controller employing high-voltage triodes in series with variable load dropping resistors allows independent voltage control of each vector electrode while requiring only one high-voltage power supply. The system also contains small horizontal and vertical time-of-flight probes which scan the beam at a distance of 100 cm. Total performance is measured using a 3 ft diam time-of-flight collector placed 190 cm away.

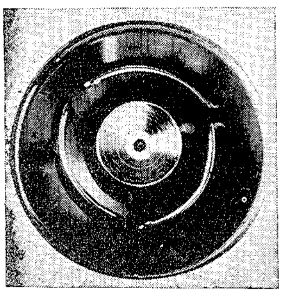

Fig. 2 Head on view of high-thrust source, three deflector electrodes, mounted in extractor.

When large numbers of measurements are made, an automatic data acquisition system is employed. The system has three main components: 1) the digital transient analyzer digitizes the TOF signal, stores it in binary, and interacts with a scope display, and 2) the Dijitscan digital converter, which converts the binary to a coded decimal form for input to 3) a local teletype terminal. The latter then communicates by telephone with a remote computer where the time-of-flight equations are computed. This process has been found to introduce a random error of about 3% into the calculations. These inaccuracies are judged to be a low price for the resulting convenience and labor savings.

Thruster Performance

Both vectorable and unvectorable thrusters have been tested. The two configurations are essentially identical except that the vector electrodes are completely removed for unvectored applications. There is little difference in performance between the two. The vectorable thruster operates at 1–2 kv higher source voltage than the unvectorable thruster.

The vectorable thruster configuration operates with source voltage between 14 and 16 kv. The most satisfactory operation has been obtained at 15 kv source voltage, where uncorrected time-of-flight beam distribution efficiencies of 65–70% have been obtained, with long life specific impulse in the 1200–1500 sec range. Table I gives a comparison of the short term operation of a vectorable high-thrust source with that of a standard 0.014-in. needle and the linear slit geometry. Nominal life times for long term operation are also shown. The superior thrust density of the high-thrust configuration is apparent.

Figures 3 and 4 show the short term performance of a vectorable source operating at 16 kv with 70% time-of-flight beam distribution efficiency, and a temperature of 25°C. Performance of the nonvectorable configuration is similar at a source voltage of 14 kv. Mass flow rate is experimentally found to be a linear function of feed pressure, and independent of source voltage. The specific impulse data has been fitted with a straight line, this being the highest degree polynominal with statistical significance in this operating range.

Impressive life time data has been obtained with each configuration. A nonvectorable thruster was run for 944 hrs, and a vectorable thruster for 1026 hrs. During each of these tests, a mass flow rate of 8–10 microgms/sec was maintained. In each case, performance was initiated at a level near that indicated by Figs. 3 and 4. As time progressed, the thrust was maintained above 90 μN in both runs. The specific impulse was kept above 1000 sec for the nonvectorable configuration, and above 1200 sec for the vectorable configuration.

Table 1 Nominal performance comparison for various colloid concepts

Parameter	Needle source	Linear slit	High-thrust source
Nearest neighbor distance (cm)	0.63	1.01	1.05
Packing density (per sq cm)	2.9	1.0	1.1
Thrust (μN per unit)	11	70[a]	110
Thrust density ($\mu N/cm^2$)	30	70	120
Relative flow conductance (per unit)	1	9.2[a]	1.4
Operating voltage (kv)	12.5	16	15
Current (μamp per unit)	10	200[a]	90
Specific impulse (sec)[b]	1500	1650	1550
Beam distribution efficiency (percent)[b]	70	70	70
Nominal demonstrated lifetime (hr)	1100	40	2000

[a] Per linear cm.
[b] Time-of-flight values.

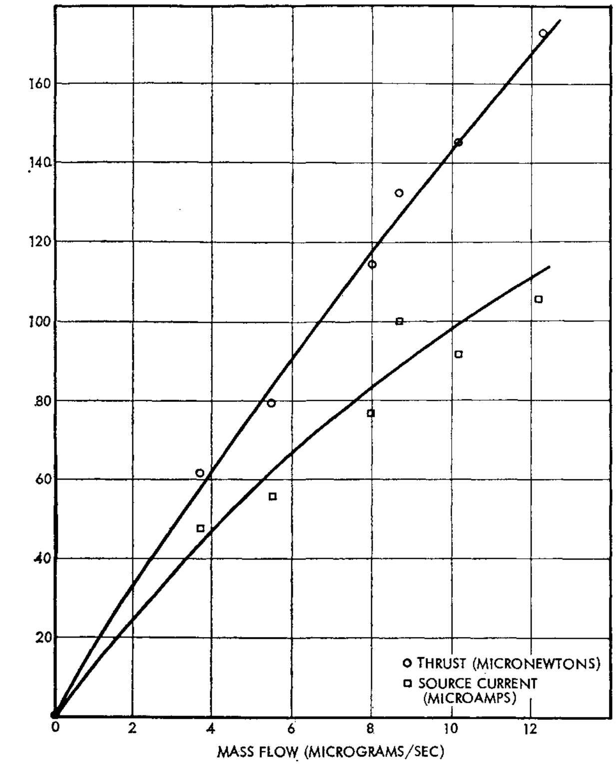

Fig. 3 Thrust and current performance data.

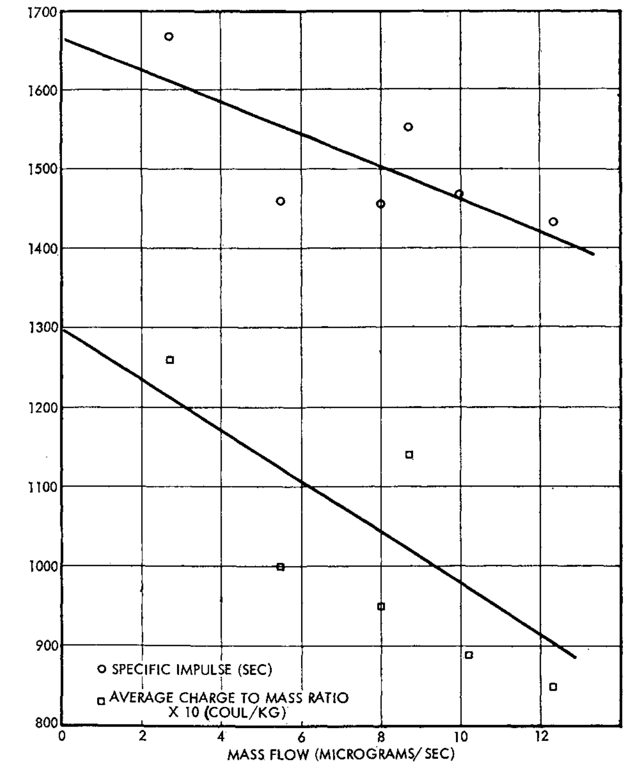

Fig. 4 Specific impulse and charge/mass.

A second life test of a vectorable thruster (Run 710501) ran for 2038 hr. Performance during the first 1000 hrs was at or above 90 μN thrust and 1250 sec specific impulse with a beam distribution efficiency of 65–70%. Source voltage was nominally 14.5 kv for the major part of the run. Figure 5 is a plot of thrust, specific impulse and beam efficiency vs operating time. At 1130 hrs, a small, reddish brown patch of

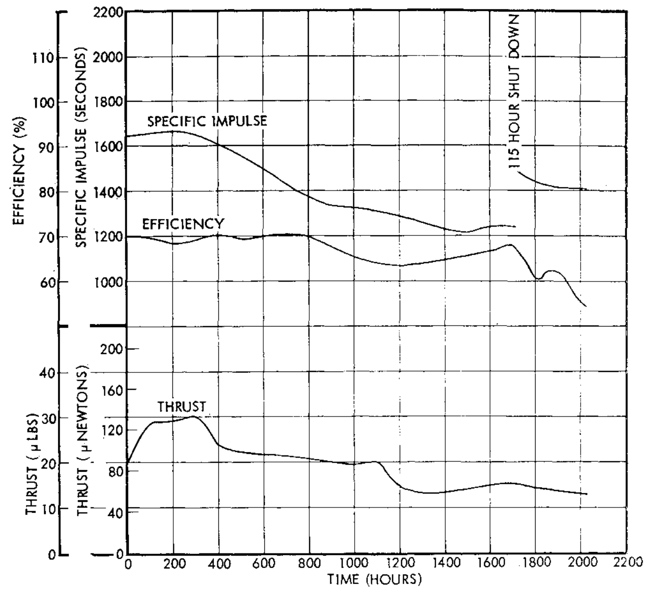

Fig. 5 1000 hr life test; specific impulse, efficiency and thrust vs time.

sediment was observed to have formed in the meniscus well. In order to maintain operational stability, it was necessary to reduce the source voltage to 13.1 kv and the mass flow to 4 μgm/sec. Later, at approximately 1400 hrs, the mass flow and source voltage were increased, and some of the performance was regained. At 1725 hrs, a laboratory accident forced shutdown of the test. The feed pressure was pumped back to maintain a negative head, and the test remained off for 115 hrs. The shutdown time is indicated in Fig. 5. The test was then successfully restarted and performance reestablished for the remainder of the test.

Although electrostatic thrust vectoring has been demonstrated, its desirability is still questionable. Electrostatic vectoring during the life test tended to reduce operational stability and probably would have decreased the ultimate thruster life. Several previous vectoring tests were terminated because of excessive vector electrode drain currents and loss of stability.

Superficially, one would expect great advantage from elimination of moving parts of electromechanical vectoring devices. There is a price to be paid, however, in the form of increased thruster complexity and additional high-voltage requirements. Vectoring response is difficult to evaluate, in that the beam profile is distorted. There is also a secondary

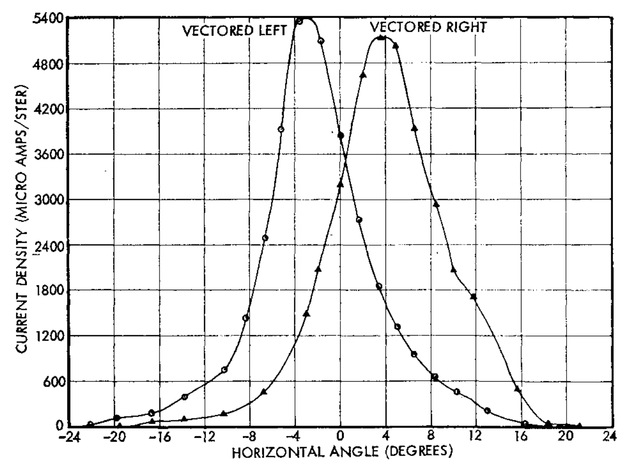

Fig. 6 Horizontal vectoring response.

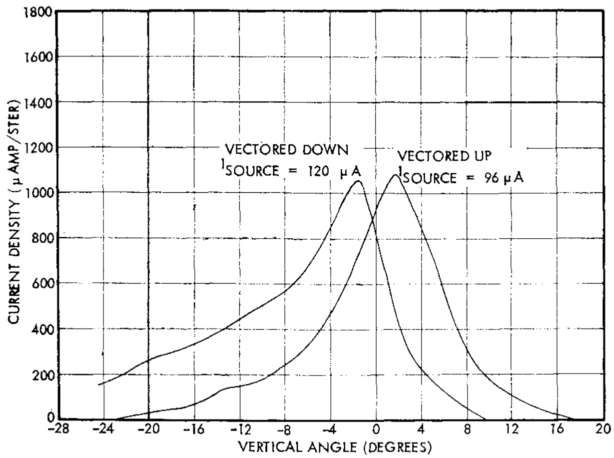

Fig. 7 Vertical vectoring response.

interaction with intrinsic beam properties, such as charge to mass ratio distribution, due to the modification of the local extraction field by the vectoring bias. Because of these effects, any attempt to precisely define the total effects of the application of electrostatic vectoring voltages will require considerable experimental effort.

The thruster vectoring response has been evaluated by taking current and time-of-flight probes across the beam's horizontal and vertical symmetry planes as a function of various vectoring voltage combinations. These measurements indicate a deflection of about 0.3–0.5°/kv differential, depending on vectoring direction. A set of horizontal vectoring data is shown in Fig. 6. A vertical vectoring scan is shown graphically in Fig. 7. Total thrust vector deflections of up to 6.5° have been measured using the probe method.

Major Problem Areas

Two major problem areas currently being explored consist of 1) the gradual buildup of sedimentary material on the emitter rims as a test progresses and 2) a complete identification and understanding of the electrostatic vectoring response of the device. Most of the work has been concentrated on the former problem, which is the older of the two. The sediment is believed to be the result of high-energy interaction and polymerization of propellant molecules caused by back-streaming electrons. It occurs only in regions where propellant lies in thin, stagnant films or in regions of high-back-streaming current density, such as at the site of a vectoring malfunction.

These conditions can be avoided by a careful analysis and improvement of procedures of thruster preparation and operation. Progress toward this end has been steady. Within the past year, thruster lifetime has been increased from roughly 100 hrs to over 1000 hrs. Further, no emitter erosion problems have been observed. Figure 8a is a photomicrograph of a clean, new source rim and should be contrasted with Fig. 8b, showing a typical segment of rim after running 1000 hrs. Small sediment patches of the order of 0.075 mm are typical.

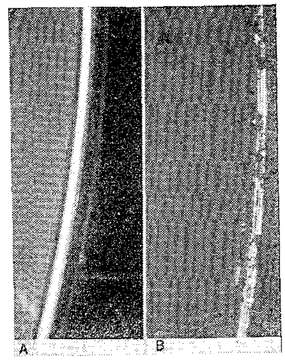

Fig. 8 Emitter rim before a) and after b) 1000 hr test.

Conclusions

The high-thrust source geometry concept has increased colloid performance in the 1200–1500 sec specific impulse range. The source is essentially a highly sophisticated thick-needle geometry. It achieves ten times greater thrust per source than attainable with conventional colloid needle thrusters. With a conservative packing geometry this produces a thrust density improvement of 300%. Life times of the order of 1000 hrs have been demonstrated for both vectorable and nonvectorable sources. The technology may be extended to high-thrust levels by building multiple source modules in the 0.5–5 μN thrust range; however, efforts to date have been concentrated on single source development. Two-axis electrostatic thrust vectoring has been demonstrated but its advantages over conventional mechanical methods remain to be proven.

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