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SERT II 1979-1981 Tests: Plasma Thrust and Neutralizer Measurements

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The SERT II (Space Electric Rocket Test II) spacecraft, launched in 1970 for a one-year mission as a test bed for an ion thruster system, continued to function as a working spacecraft through May 1981. As a result, an opportunity existed to obtain extensive thruster system test data over a period of more than a decade. This paper presents results obtained in the last 2½ years of this test period. A new mode of thrusting, using only the plasma of the main discharge chamber, was discovered and its thrust performance documented. This paper, in addition, presents results of unique neutralizer tests using, first, a distant neutralizer electron source; second, electrons from the main discharge chamber of a distant thrust; and, finally, no neutralizer whatever.

Nomenclature

I	= current, mA
N_i	= ion plasma density, ions/cm^3
neut	= neutralizer
main	= main discharge of thruster
S/C	= spacecraft
T/S-1	= thruster system 1
T/S-2	= thruster system 2
V	= voltage, V
V_S	= space plasma potential (assumed = 0 V)

Introduction

THE SERT II spacecraft was launched with a primary objective of demonstrating long-term operation of a space electric thruster system.[1] Progress towards that objective was completed late in 1970 when each of two ion thruster systems on board developed a high-voltage grid short. The spacecraft, although, was still functional and cathode restart/propellant system tests were performed in 1973-74.[2] A spacecraft spin-up maneuver in 1973 caused the grid short of one thruster to clear, and subsequent tests in 1974 showed normal operation of that thruster. Tests in the mid-1970s, however, were limited to brief test periods because the Earth's shadow eclipsed the spacecraft solar array each orbit. In early 1979 through May 1981 the orbit became a continuous sunlight orbit again, continuous testing exhausted the ion thruster system propellant tanks, and no more thruster operation was possible. The spacecraft continued to function until its transmitters were turned off by ground command in June 1981.

This paper presents the direct thrust performance measurements of a newly discovered "plasma mode" of operation, and unique neutralizer tests using various manners of electron sources. A companion paper[3] presents ion thruster system performance and component durability data obtained during the last 2½ years of testing. Details of the spacecraft subsystem performance may be found in Ref. 4. Reference 5 contains a systematic listing of beam probe data and a study of plasma effluent of the two thruster systems.

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Apparatus and Procedure

The SERT II spacecraft is shown in Fig. 1. It consists of an Agena stage rocket with a 1.5-kW solar array on one end and two experimental ion thruster systems on the opposite end. Further description of the spacecraft and its operation may be found in Refs. 2, 5, and 6. A thruster system contains an ion thruster together with Hg-loaded propellant tanks mounted on gimbals. A thruster power conditioning and control box is located inside the spacecraft body. Each thruster system has a hot-wire probe that can be swept through the ion exhaust beam and measure its plasma potential profile. The companion paper[3] describes the ion thruster system and its operation in detail.

Hot-Wire Probes

The SERT II spacecraft was designed with three hot-wire emissive probes to measure plasma potentials.[7] One probe, which burned out in 1971, was at the end of 1.5-m-long beam protruding ahead of the S/C body. The other two probes were each at the end of an arm that rotated it into and out of each ion beam. The two beam probes are shown in Fig. 2. Beam probe 1 was jammed and remained stationary in a position fully away from the beam center, but was electrically operative. Beam probe 2 functioned normally. When commanded, it began rotating and was heated at the same time. The probe voltages were data as received from the S/C and were relative to the S/C frame. All plasma potentials shown on the figures were relative to the space plasma potential, which was assumed zero. Details of the probe operation may be found in Ref. 5 or 7.

V9 Bias Supply

The V9 supply was designed to place a bias voltage between the neutralizer cathode and S/C ground. In addition to zero voltage, four nominal bias voltages of ±25 and ±50 V were available. The common of the bias supply was connected to the S/C ground, and the output then drove the neutralizer cathode either + or − with respect to the S/C frame. Neutralizer emission current was required to produce positive bias. At times, when there was little or no neutralizer emission, the nominal positive V9 voltage did not appear on the neutralizer. The I9 telemetry read emitted electron current from the S/C ground through the neutralizer cathode to space plasma. If electron flow was in the opposite direction, I9 telemetry would read zero.

Telemetry Data Accuracy

All S/C data were in the form of 0-63 counts, but each parameter has its own scale factor. Table 1 gives the value of

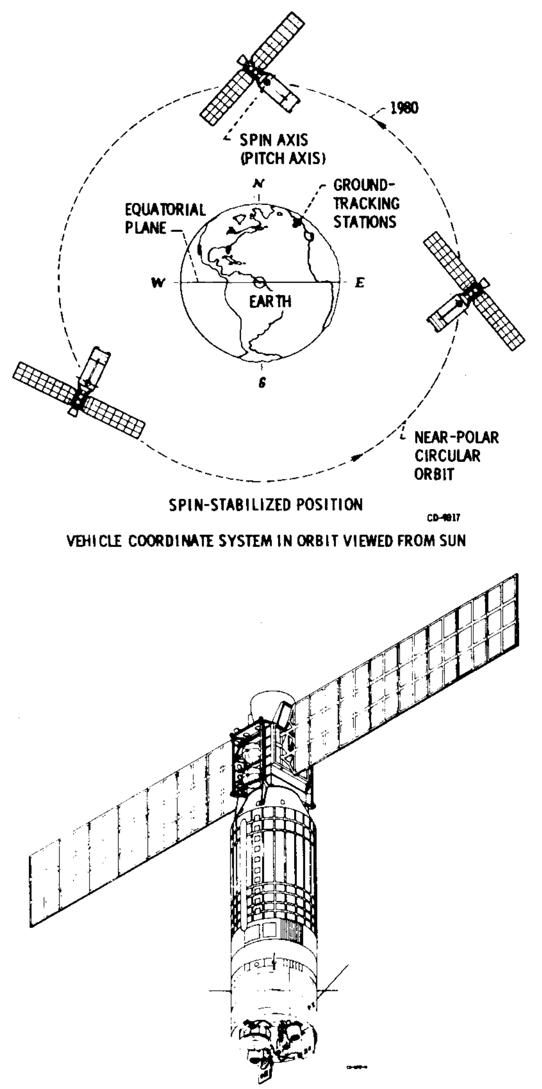

Fig. 1 SERT II spacecraft in orbit (artist's conception).

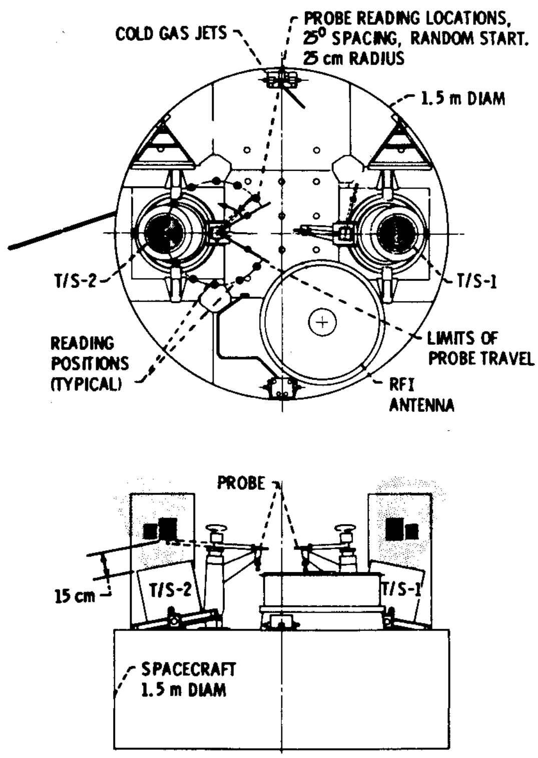

Fig. 2 SERT II spacecraft drawing showing beam probe location.

Table 1 Spacecraft telemetry values

Parameter	1-count value
I5	5 mA
I6	0.05 mA
I9	7 mA
V9	2 V
V10	0.5
Probe voltage	2.4 V

1-count change in each parameter. The uncertainty is +0.5 count.

Plasma Beam Thrust

Plasma beam thrust is a new SERT II thrust operating mode (utilizing only the main discharge chamber plasma) that was discovered by chance in late 1979. At that time the T/S-1 main discharge was turned on and allowed to run continuous for endurance testing. After several days it was noticed that the spacecraft spin rate was changing at a rate greater than normal. T/S-1 was producing thrust, about 0.8 mN, with no (V5 and V6 turned off, see Fig. 3) voltages on the accelerator grids. Furthermore, no ion beam was indicated by telemetry measuring circuits.

What apparently happened was that the main discharge (V4) produced a mercury plasma at the level of the V4 voltage, 40 V. This plasma diffused through the accelerator grids, carrying an equal number of electrons and ions. Once by the grids the ions were accelerated through a 40-V sheath, producing a thrust beam. Electrons somehow were either carried along by the ion space charge or diffused into space plasma.

T/S-1 was producing thrust, and the main discharge supply was the only supply that could give energy to produce a thrust beam. Subsequently, other tests were run at lower discharge voltage, which dropped the thrust level, and with the other thruster system, which produced about the same level of thrust. The thrust measured for 16 plasma beam thrust tests on SERT II are detailed in Ref. 8. Also in Ref. 8 are thruster operating conditions, estimated flow rate, estimated floating levels of the V5 and V6 supplies, and a calculated plasma beam ion current. The beam calculation assumed a one-dimensional ion beam. The actual plasma beam has some degree of divergence, which if incorporated in the calculated ion current, would increase the ion current (perhaps by 20%). A qualitative idea of the divergence may be seen in Fig. 4. The nominal performance of the thruster operating in the plasma thrust mode follows: thrust = 0.8 mN, I_{sp} (corrected) = 300 s, power (discharge only) = 80 W, flow rate = 1 g/h, and power/thrust = 100 W/mN.

The plasma potential of the plasma beam for T/S-2 is shown in Fig. 4 for two cases of neutralizer keeper discharge on and off, respectively. The no bias curve shows a broad, but relatively flat potential profile as compared to the ion beam profiles (shown later). When the neut-2 was biased to −44 V, the potential edge of the plasma beam becomes better defined and a negative well was formed on either side. Biasing of the neutralizer exhibited potential control of the spacecraft as if the normal ion beam were operating. The design of the bias supply[5] did not permit positive bias while in the plasma beam mode, so negative spacecraft voltages were not demonstrated.

Distant Neutralization

Reference 5 presented early data on distant neutralization, a term used to describe neutralization of T/S-2 beam by electrons emitted from the neutralizer of T/S-1, almost 1 m away. Figure 5 shows a diagram of possible ion currents and

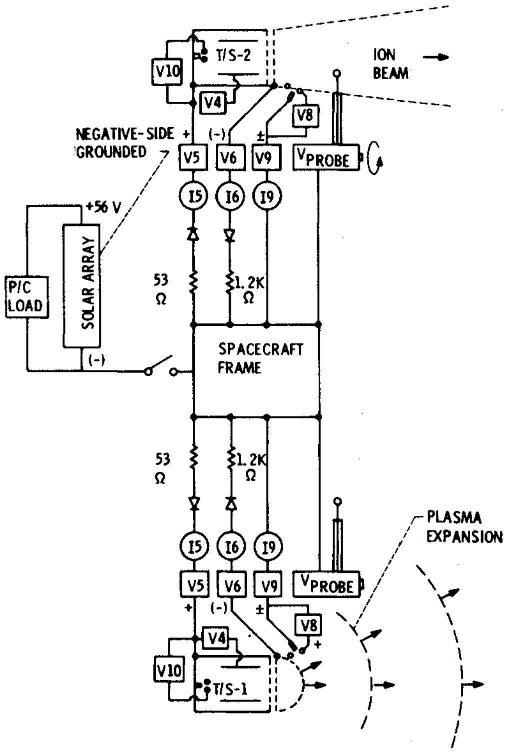

Fig. 3 SERT II power supply and solar array circuits.

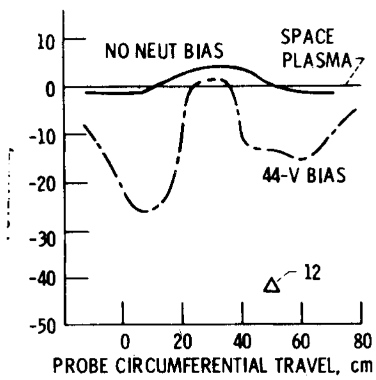

Fig. 4 Measured plasma potential of thruster-2 in plasma thrust mode.

plasma densities while in distant neutralization. One result of Ref. 5 that was difficult to explain was that the neutralizer coupling voltage (between neutralizer and beam center) was lower in the distant coupling mode than for normal neutralization. Reference 9 suggested a model for coupling voltages that explained the relative ease (lower coupling voltage) of distant neutralization. This model used the thruster external magnetic fields and showed that neut-2 emission must cross magnetic lines to enter its beam plasma, while neut-1 emission can follow (without crossing) magnetic lines in a path reaching to the ion beam 1 m away.

The fraction of emission coming from either neutralizer could be adjusted by varying a bias potential (V9, Fig. 3) to either neutralizer cathode. Figure 6 shows how this fraction changes with bias voltage in addition to corresponding changes in beam voltage and spacecraft voltage.

The data of Fig. 6 show that for no (zero) bias voltage, most of the neutralizer emission came from the neutralizer near the ion beam. For 83-mA beam data, all emission could be cut off from neut-2 by applying a +34-V bias to neut-2. Similarly, a bias of +6 V on neut-1 (neut-2 at no bias) cut off all emission from neut-1. For 200-mA beam data, the neut-2 bias was set at its maximum value (+46 V), but still about

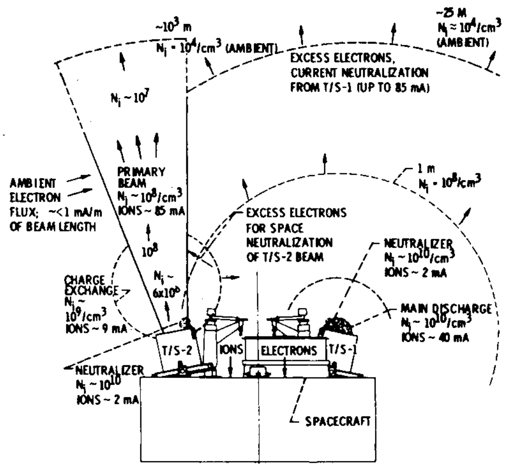

Fig. 5 Spacecraft plasma current diagram.

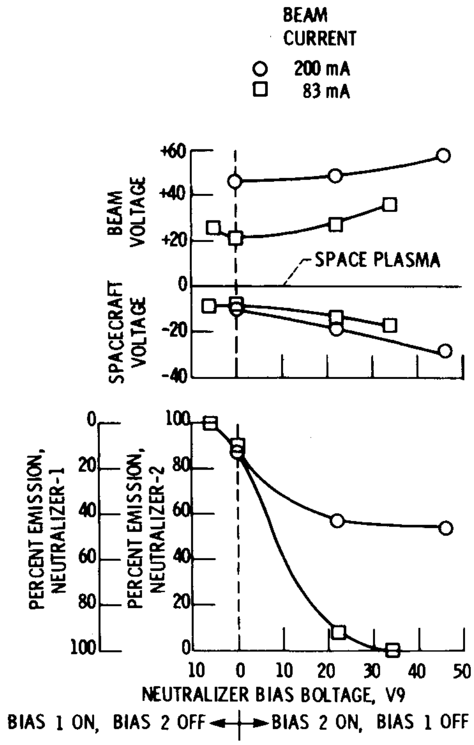

Fig. 6 Cross neutralization of thruster-2 at two beam current levels.

one-half the emission came from neut-2. The lack of complete cutoff was probably due to the higher beam plasma voltage (acting like a natural anode) at 200-mA beam and a fixed bias limit. The spacecraft voltage and beam voltage react to neutralizer bias as expected from Ref. 4 or 7. (Space plasma potential is defined as zero.)

The increased difficulty of distant neutralization at 200 mA means that distant neutralization of a multiple thruster array, particularly at higher beam current, may not be as readily accomplished as first stated in Ref. 5.

No Local Neutralizer

The distant neutralization data taken in early 1979[5] was always modified by the fact that there was no way to operate an ion beam without having its local neutralizer also turned on. Simulated off conditions were achieved by applying positive bias to the local neutralizer cathode, but the onboard command sequences did not provide for separate disabling of the neutralizer. Therefore a test plan was made to disable the neutralizer by operating it long enough to empty its mercury propellant tank. Then, the neutralizer was incapable of

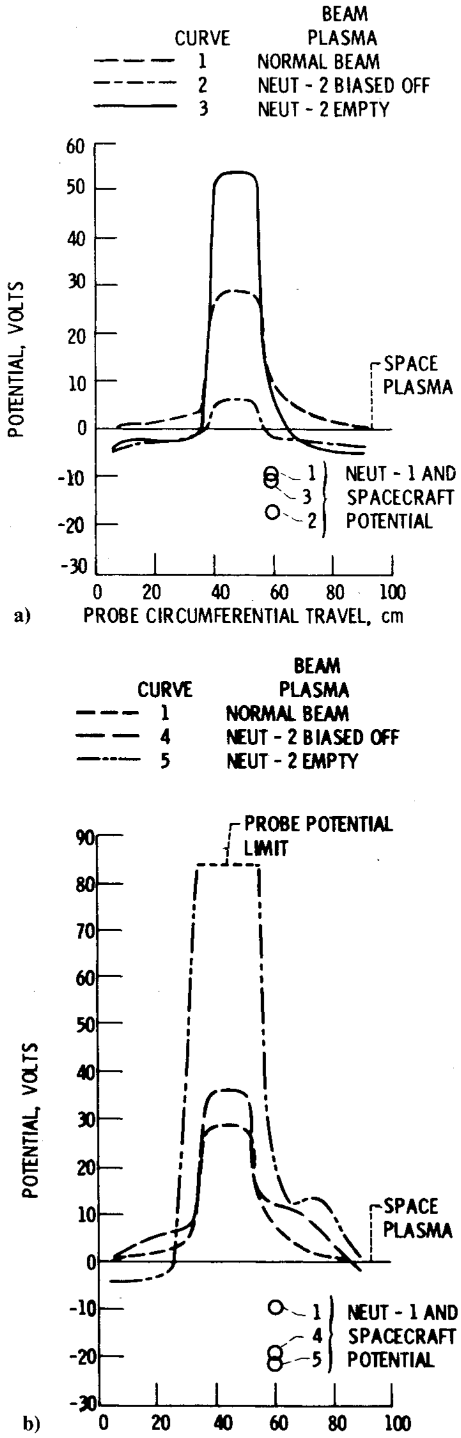

Fig. 7 Beam plasma potential plots for various types of neutralization of thruster-2 beam. a) From neut-1 with main-1 on; b) from neut-1 without main-1 on.

significant emission because there was no mercury flow to establish a hollow cathode discharge. Under this condition the keeper electrode was at high (7 250 V) starting voltage and the tip heater was at maximum power. Thermionic emission at the maximum power temperature (1100°C) was less than 1 mA.

After the neut-2 tank was emptied on day 122, 1980, distant neutralization tests were run in which 1) the main-1 and neut-1 discharges were turned on to neutralize the ion beam from T/S-2 (Fig. 7a), or 2) just neut-1 turned on (Fig. 7b). Later, 3) when the neut-1 propellant tank was empty, neutralization was accomplished from just the main-1 discharge, but with higher coupling voltage than indicated in Fig. 7a or 7b. Figure 7 contains plots of ion beam plasma potential profiles taken with the movable hot-wire probe of T/S-2. Voltage levels for the spacecraft and neut-1 are also shown, and were determined by the probe for T/S-1, which was in a fixed position[5] midway between T/S-2 and T/S-1. Thruster operating conditions for Fig. 7 as well as Fig. 4 may be found in Ref. 3.

Figure 7a results show three curves: 1) normal operation with local neutralization, 2) distant neutralization with neut-2 biased off, and 3) distant neutralization with neut-2 empty. As stated in the previous section, curve 2 shows a drop in beam plasma potential and coupling voltage when both neutralizer discharges were operating, although all emission seemed to be coming from the distant neutralizer. Curve 3 shows a 25-V increase in beam plasma potential with the local (neut-2) neutralizer empty. Interestingly, curves 1 and 3 have about the same spacecraft potential, and the 34-V positive bias of neut-2 (curve 2) lowered the spacecraft potential by 10 V.

The following hypothesis is offered by Domitz[5] to explain the coupling voltages observed in Fig. 7a: Space-charge neutralization of an ion beam may require only a small (~1 mA) number of electrons which become trapped in the positive well of the beam plasma. The only electrons that need to be added are equal to those lost from this well. Current neutralization may be achieved by other paths external and perhaps far downstream from the local neutralizer. For example, neutralizer electrons could flow into the space plasma and other space plasma electrons could current-neutralize the beam.

Curve 2, with emission biased to "zero," may have emitted a net current of 3 mA and still have shown zero counts on the telemetry channel. The neut-2 keeper potential was 28 V above spacecraft potential and therefore a few volts above the "wing" plasma of curve 2. Hence electrons from the keeper discharge could have been easily drawn into the beam to provide space-charge neutralization, while neut-1 emission was providing the bulk of the current neutralization to space plasma. When the local neutralizer tank (neut-2) was empty and no keeper discharge was present, space-charge electrons were drawn from further away and a higher beam plasma potential resulted.

Figure 7b shows the effect of eliminating the plasma produced by the main-1 discharge. Without this additional plasma density, the beam plasma potential must increase to draw sufficient electrons to itself. Figure 7b shows a normal beam profile for reference, together with two corresponding neut-2 curves, but with the main-1 discharge off. In curve 5 (neut-2 empty) the beam plasma potential is not only high enough to exceed the design range of the probe, it has considerably broadened in width, and the spacecraft potential was lowered. All these trends were apparently caused by the need for neutralizing electrons and the relative impedance (no main-1 discharge plasma) to electron diffusion.

The operating conditions of both curves 3 and 5 were maintained for two days to obtain a thrust measurement with this type of neutralization. The result was a thrust of 9.9 mN (±5%) for curve 3 and 10.0 mN (±3%) for curve 5. Both these values were essentially the same as for normal neutralization-measured thrust[4] of 10.0 mN (±3%). Apparently no appreciable beam divergence was introduced by the distant neutralization, nor did the greater beam potential affect the thrust.

The most dramatic case of operation with no local neutralizer occurred when the conditions of case 3 above were being attempted and T/S-1 shut off completely owing to a 2-min overload integration device incorporated into the system. Surprisingly, T/S-2 continued to operate at 85-mA beam current with no source of net electron emission. This condition lasted for 53 min and data were obtained from the onboard tape recorder. Eventually high-voltage trips occurred to T/S-2 and the overload integrator device shut T/S-2 down. The above conditions were repeated three times, but the system never remained operating long enough to obtain a spin-rate thrust measurement. The probes were at their maximum values. This indicated a spacecraft potential of < -106 V. The actual value of spacecraft potential could have been any magnitude up to the positive high voltage (screen) of 3150 V. At such large negative spacecraft potentials the thrust should be severely reduced by beam turnaround. Surprisingly, the accelerator grid, which was -1400 V with respect to the already negative spacecraft, did not attract enough ions to trip its overload value of 60 mA. The actual I6 value was 33 mA. Apparently, the beam plasma shielded the accelerator grid and the remaining (85-33) mA of beam returned to other parts of the spacecraft where it was not sensed by telemetry.

The above case has not been fully modeled analytically, but space ions returning to the spacecraft were probably the order of 1 mA. Charge-exchange beam ions might have contributed an estimated 9 mA (Fig. 5), still leaving about 40 mA returning to other parts of the spacecraft or thruster ground shield. This flux of returning ions did no apparent damage to the spacecraft, which functioned normally during the beam turnaround operation. T/S-2 itself might have become a casuality to beam turnaround, because a day later, while operating T/S-2 (neutralized by neut-1 and main-1) a permanent high-voltage thruster body short-to-ground developed. High-voltage shorts are discussed in a companion paper,[3] but note that this short was not the same as the 1970-type which was a screen-to-accel grid short.

Conclusions

A new mode of thrusting was discovered while operating the SERT II ion thruster in a discharge-only condition. While not as efficient a mode as when using normal high-voltage acceleration, the new "plasma mode" of thrusting has future application for spacecraft attitude control or as an contingency following high-voltage failure. Extended tests were also conducted to study ion beam neutralization, plasma efflux between ion thruster and spacecraft, and beam neutralization from a distant (1 m away) neutralizer source. Under selected conditions, beam neutralization was more easily accomplished by the distant source. One test was even conducted with no neutralizer source.

References

[1]Kerslake, W.R., Goldman, R.G., and Neiberding, W.C., "SERT II: Mission, Thruster, Performance and In-Flight Thrust Measurements," *Journal of Spacecraft and Rockets*, Vol. 8, March 1971, pp. 213-224.

[2]Kerslake, W.R. and Finke, R.C., "SERT II Spacecraft Thruster Restart, 1974," *Journal of Spacecraft and Rockets*, Vol. 12, Dec. 1975, pp. 780-782.

[3]Kerslake, W.R. and Ignaczak, L.R., "SERT II 1979-1981 Tests: Ion Thruster Performance and Durability," *Journal of Spacecraft and Rockets*, Vol. 19, May-June 1982, pp. 241-245.

[4]Kerslake, W.R. and Ignaczak, L.R., "SERT II 1979 Extended Flight Thruster System Performance," AIAA Paper 79-2063, Oct. 1979.

[5]Kerslake, W.R. and Domitz, S., "Neutralization Tests on the SERT II Spacecraft," AIAA Paper 79-2064, Oct. 1979.

[6]Ignaczak, L.R., Stevens, N.J., and LeRoy, B.E., "Performance of the SERT II Spacecraft after 4½ Years in Space," NASA TM X-71632, 1974.

[7]Jones, S.G., Staskus, J.V., and Byers, D.C., "Preliminary Results of SERT II Spacecraft Potential Measurements Using Hot-Wire Emissive Probes," AIAA Paper 70-1127, Aug. 1970; see also NASA TM X-52856, 1970.

[8]Kerslake, W.R. and Ignaczak, L.R., "SERT II 1980 Extended Flight Thruster Experiments," AIAA Paper 81-0665, April 1981.

[9]Kaufman, H.R., "Plasma Physics Analysis of SERT II Operation," Colorado State Univ., Fort Collins, Colo., Jan. 1980; see also NASA CR-159814, 1980.