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PULSED INDUCTIVE THRUSTER DEVELOPMENT
(ADVANCED ELECTRIC PROPULSION TECHNOLOGY - HIGH THRUST)
Volume 2. Supplement

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Supplement to Final Report for the Period November 1980 - June 1982

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The AFRPL Technical Services Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

Prepared for

AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTOR OF SCIENCE AND TECHNOLOGY
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NOTICE

FOREWORD

The work reported herein was supported by the Air Force Rocket Propulsion Laboratory at Edwards Air Force Base. It was monitored by Lt M. Brasher and Lt W. Schmidt. The program was conducted by TRW Defense and Space Systems Group, Inc. at its Space Park Facility in Redondo Beach, California. Dr. C. L. Dailey was the Program Manager, Professor R. H. Lovberg served as consultant and W. P. Goldstein was responsible for detail design and fabrication of the thruster and test equipment. Theoretical analysis and data system software development were carried out by Professor Lovberg.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results of an experimental investigation of the operation and efficiency of a large impulsive plasma thruster. The thruster uses a one-meter diameter flat spiral coil through which current is pulsed from a 4000 Joule capacitor bank using a spark gap switch. The plasma is driven through inductive coupling rather than with electrodes so as to avoid erosion and energy loss mechanisms that might be undesirable for spacecraft uses. The object of this work was to verify the results of the final report,

(AFRPL-TR-80-67, to which this is a supplement), and establish more data on thruster efficiency as a function of specific impulse. The original final report indicated the thruster's efficiency was 45% at 1570 sec isp. This supplement confirms those figures and reports additional performance figure of 50% at 1590 sec Isp, 62% at 1960 Isp, and 67% at 2250 sec Isp.

ADVANCED ELECTRIC PROPULSION TECHNOLOGY
HIGH THRUST

SUPPLEMENT TO FINAL REPORT

Contract No. F04611-79-C-0058 15 April 1982

Prepared for

Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California 93523

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FOREWORD

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SUMMARY

Reference 1 describes the measurement of efficiency and specific impulse of the pulsed inductive thruster at a single operating condition. The result was 45.0% at 1570 seconds I_{sp}. Subsequent work, described herein, was initiated to verify this result, improve the measurement accuracy and extend the range of η versus I_{sp} data. Thruster modifications included covering the surfaces exposed to plasma radiation with glass, re-calibration of probes, use of a different procedure to subtract spurious current density signals, and a direct measurement of mass accelerated by the thruster. Also, the propellant injection nozzle was moved away from the coil so that the gas could be injected toward the coil, as opposed to the purely radial gas injection used previously[1].

Data measured with these modifications are:

η (%)	I_{sp} (sec)
50	1590
62	1960
67	2250

Further work is needed to verify the impulse measurements by means of a thrust balance and to investigate the possibility of mass addition, other than the injected propellant, to the accelerated plasma.

INTRODUCTION

The thruster and measurement technique are described in detail in Reference 1. A one-meter diameter, flat, spiral coil is used to drive the plasma through inductive coupling rather than with electrodes so as to avoid erosion and energy loss mechanisms that might be undesirable for spacecraft uses. Impulse developed during the discharge of a 20 μ-Farad capacitor bank through the coil is measured by means of miniature plasma probes. These probes measure local azimuthal current density and radial magnetic field. Their product is the local force density which is integrated over the radial and azimuthal extent of the accelerated plasma, and over the discharge duration, to obtain the impulse.

The primary purpose of the present additional effort with this thruster was to extend the data base and improve its accuracy.

DISCUSSION

Thruster Modification

The thruster with the modified propellant injection nozzle is shown in Figure 1. The valve exit has been moved in front of the coil so that the propellant is injected back against the coil face at a 45° angle. This produces an axial velocity roughly equal to the radial velocity instead of the purely radial velocity of the previous nozzle[1]. The coil is covered with a 1/8-inch thick glass plate; glass microscope slides are attached to the inside of the outer collar and to the outside of the cylinder supporting the nozzle.

Probe Modification

As a check on probe measurement accuracy, additional magnetic field and current density probes were built, calibrated and used for thrust measurements. There were no distinguishable differences between the old and new magnetic field probe data. The new current density probe, however, gave substantially different results. This was a carefully balanced probe, wound with an equal number of turns on each side of the lead wires (see Reference 1) to minimize spurious electric field effects. A careful com-

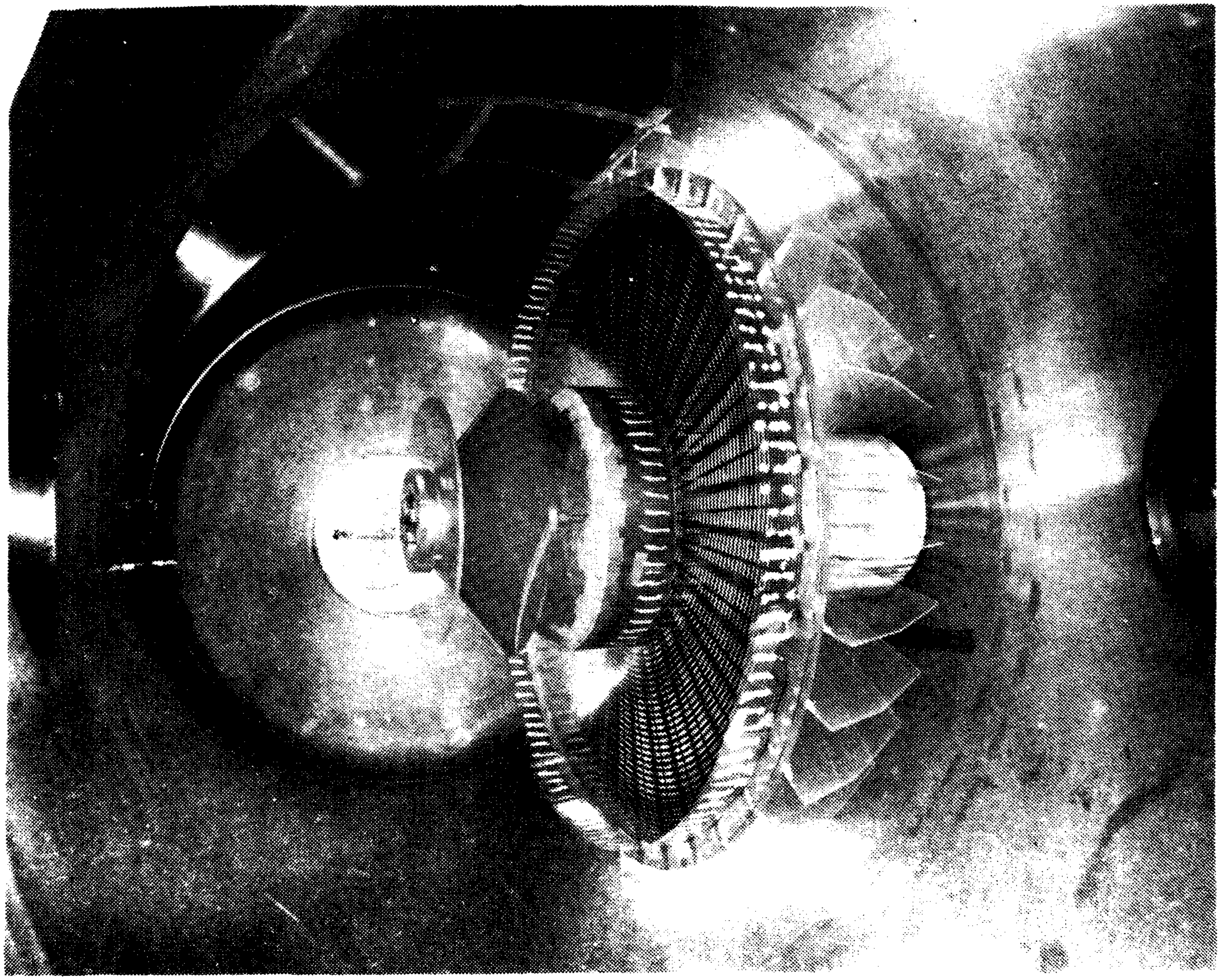

Figure 1. Photograph of Thruster in Vacuum Chamber Showing Elevated Propellant Injector and Glass Covered Surfaces

parison of data from both probes showed a noticeable, but small, electric field effect as well as a small sensitivity to the magnetic field. The former appeared near the end of the current density pulse with a small duration compared to that of the current density pulse. However, the magnetic field signal persisted 4 to 5 times as long as the current pulse. This spurious indication of a small current density at a time when the magnetic field was large, produced a substantial integrated impulse error. This error source was eliminated in subsequent testing by running three sets of probe surveys for each impulse determination: one for the magnetic field measurement, one with the current density probe (using the original probe) and the final one with the window of the latter probe covered with a piece of Scotch tape so that the probe recorded only the total error signal due to both electric and magnetic field effects. By differencing the two sets of current density probe data, the correct plasma current density measurements were obtained.

Propellant Measurement

In Reference 1, the propellant mass Δm was estimated as 75% of the mass stored in the calculated volume of the valve plenum. An error in determining this mass inversely effects both efficiency η and I_{sp}. Since the efficiency is

$$\eta = \frac{1/2\ \Delta m\ V^2}{J_o} = \frac{1/2\ \Delta I(g\ I_{sp})}{J_o} \tag{1}$$

where J_o is stored energy, and the impulse ΔI is

$$\Delta I = \Delta m(g\ I_{sp}) \tag{2}$$

it follows that

$$\frac{\eta}{I_{sp}} = \frac{g}{2}\ \frac{\Delta I}{J_o} \tag{3}$$

Since both impulse and stored energy are accurately known, it follows that the slope defined by Equation (3) is also accurately know, independently of the accelerated mass. If the true mass is larger than expected, both I_{sp}

and η are decreased by the same factor. Thus in a plot of η versus I_{sp}, both points would lie on the same straight line through the origin. And since that line is nearly tangent to the η versus I_{sp} relation in the I_{sp} range of 1500 to 2500 seconds, it is seen that an error in accelerated mass has little effect on determining the η versus I_{sp} relation for that I_{sp} range.

However, in order to reduce the errors associated with present measurements, it seemed desirable to attempt an absolute calibration of the gas density probe. The probe consisted of a miniature pentode (CK 5702) with the envelope removed and the tube operated as an ionization gage[1]. The calibration was done by plotting the probe signal against a McLeod ge measurement of the pressure produced by dumping a small amount of ion into the closed vacuum chamber. Since both the shape and sensitiv of the resulting calibration were found to differ from one tube to ther, a calibration was run for each tube prior to using it for the puls gas density distribution measurement. Results of a typical gage tube calibration are shown in Figure 2. Separate calibrations were made in this manner each time a change was made in the valve (e.g., altered seal spring force or nozzle fairing). Probe measurements were made at 6 equally spaced radial stations from 25 to 50 cm and axially at z = 1.5 and 3 cm and at 2 cm increments to z = 15 cm and integrated over this volume to determine mass as a function of time.

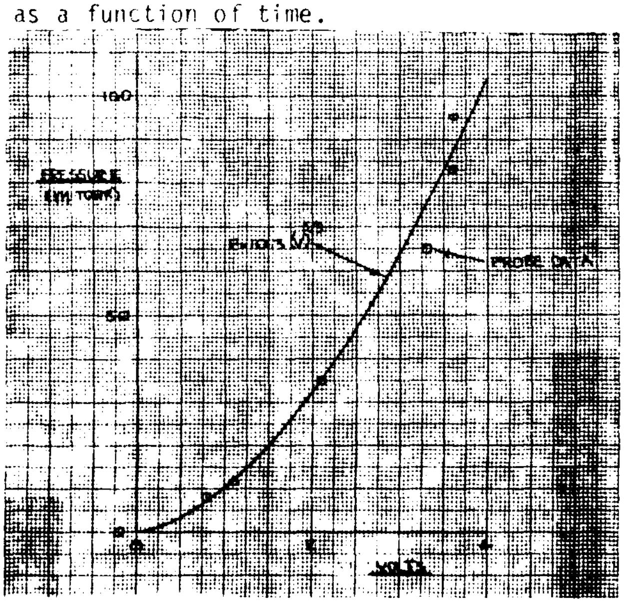

Figure 2. Gas Density Probe Calibration

Test Results

Table 1 summarizes results of 29 tests with this thruster. The test variables were valve plenum pressure P_0, capacitor voltage V_0, nozzle configuration (radial flow nozzle or elevated nozzle), and the cover used for the coil and the inner and outer cylindrical surfaces facing toward the plasma volume.

Solid symbols are shown in Table 1 for uncorrected current density probe data. The tests for which the more accurate difference method was used to find the current density are indicated with open symbols. The flagged symbols used for Runs 30 through 34 indicate tests for which a local obstruction was found in the valve exit slit due to an improper joint between the valve and the inside conical surface of the nozzle. The term "clean exit", in Table 1, indicates that this condition was corrected for the runs after Run 34. Run 36 was a repeat of Run 35 with the entire valve/nozzle assembly rotated 180° to check for a possible asymmetry in the thruster operation. A point by point comparison was made by overlaying the new probe data on corresponding data from Run 35 that were recalled from the computer data bank. As noted in Table 1, no asymmetry was observed. The data overlay for both the B_r and J_θ probes was essentially perfect.

Figure 3 shows all of the data points listed in Table 1. All of the solid points are in error because of the current density probe problem already described. Additional errors due to valve problems occurred in Runs 16, 22, 23, 24 and 25. The very high efficiency seen for Run 14 was thought to suggest that ablation might be occurring at the higher voltage (25 kV) used for that run. The 1/8-inch thick glass coil cover was installed at that point and tested in Run 15 at the same conditions. Further changes in surface covers were then made at 20 kV, with the elevated valve and nozzle geometry, Runs 16 through 19. Because of the errors present in all of the tests indicated by solid symbols, none of the apparent trends are regarded as significant. The possibility of mass, other than argon, in the discharge remains open and will require further work.

The open symbols indicate valid tests. The flagged symbols, however, should be disregarded because of the valve exit slit obstruction mentioned earlier which apparently reduced the measured impulse. This effect is seen

Table 1. Test Summary

Run No.	P_o (psia)	V_o (kV)	Δm $\times 10^{5}$ (kg)	ΔI (N-s)	η	I_{sp} (sec)	Nozzle	J_o Probe	Cover	Valve	Symbol
8	95	20	1.54	0.230	43	1520	Radial	First	All Mylar		●
10	53	15	0.86	0.094	23	1120	Radial	First	All Mylar		●
11	53	20	0.86	0.182	48	2170	Radial	First	All Mylar		●
12	110	20	1.77	0.212	32	1220	Radial	First	All Mylar	Leaky	●
13	25	20	0.41	0.137	58	3450	Radial	First	All Mylar		●
14	54	25	0.87	0.311	89	3650	Radial	First	All Mylar		◐
15	53	25	0.86	0.292	80	3480	Radial	First	Glass Coil, Mylar Inner, Mylar Outer		◐
16	82	20	1.32	0.256	62	1980	Elevated	First	Glass Coil, Mylar Inner, Mylar Outer		◢
17	82	20	1.32	0.249	59	1920	Elevated	First	Glass Coil, Mylar Inner, Kapton Outer		◢
18	82	20	1.32	0.218	55	1690	Elevated	First	Glass Coil, Mylar Inner, Glass Outer		◢
19	92	20	1.32	0.247	58	1910	Elevated	First	Glass Coil, Kapton Inner, Glass Outer		◢
22	84	20	1.35	0.170	27	1280	Elevated	Second	Glass Coil, Glass Inner, Glass Outer	Too Tight	▼
23	84	20	1.35	0.173	28	1310	Elevated	Second	Glass Coil, Glass Inner, Glass Outer	Leaky	▼
24	84	20	1.35	0.178	23	1350	Elevated	Second	Glass Coil, Glass Inner, Glass Outer	Leaky	▼
25	84	20	1.35	0.202	38	1530	Elevated	First	Glass Coil, Glass Inner, Glass Outer	Leaky	▲
28	55	20	0.89	0.131	24	1510	Elevated	Second	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	▼
29	55	20	0.89	0.285	115	3290	Elevated	First	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	▲
30	55	20	0.89	0.189	50	2200	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	△
31	55	24	0.89	0.296	86	3400	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	△
32	55	18	0.89	0.137	33	1570	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	△
33	68	20	1.03	0.200	49	1980	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	△
34	80	20	1.29	0.232	52	1840	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Locked Pintle	△
35	80	20	1.29	0.259	65	2050	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Clean Exit	△
36	80	20	1.29	No Asymmetry Observed			Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Rotated 180°	△
37	80	20	1.29	0.254	63	2010	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Recalibrated	○
38	80	20	1.29	0.257	62	1960	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Recalibrated	○
39	80	18	1.29	0.209	50	1590	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Recalibrated	○
40	80	22	1.29	0.295	67	2250	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Recalibrated	○
41	80	24	1.29	0.351	80	2670	Elevated	Difference Method	Glass Coil, Glass Inner, Glass Outer	Recalibrated	○

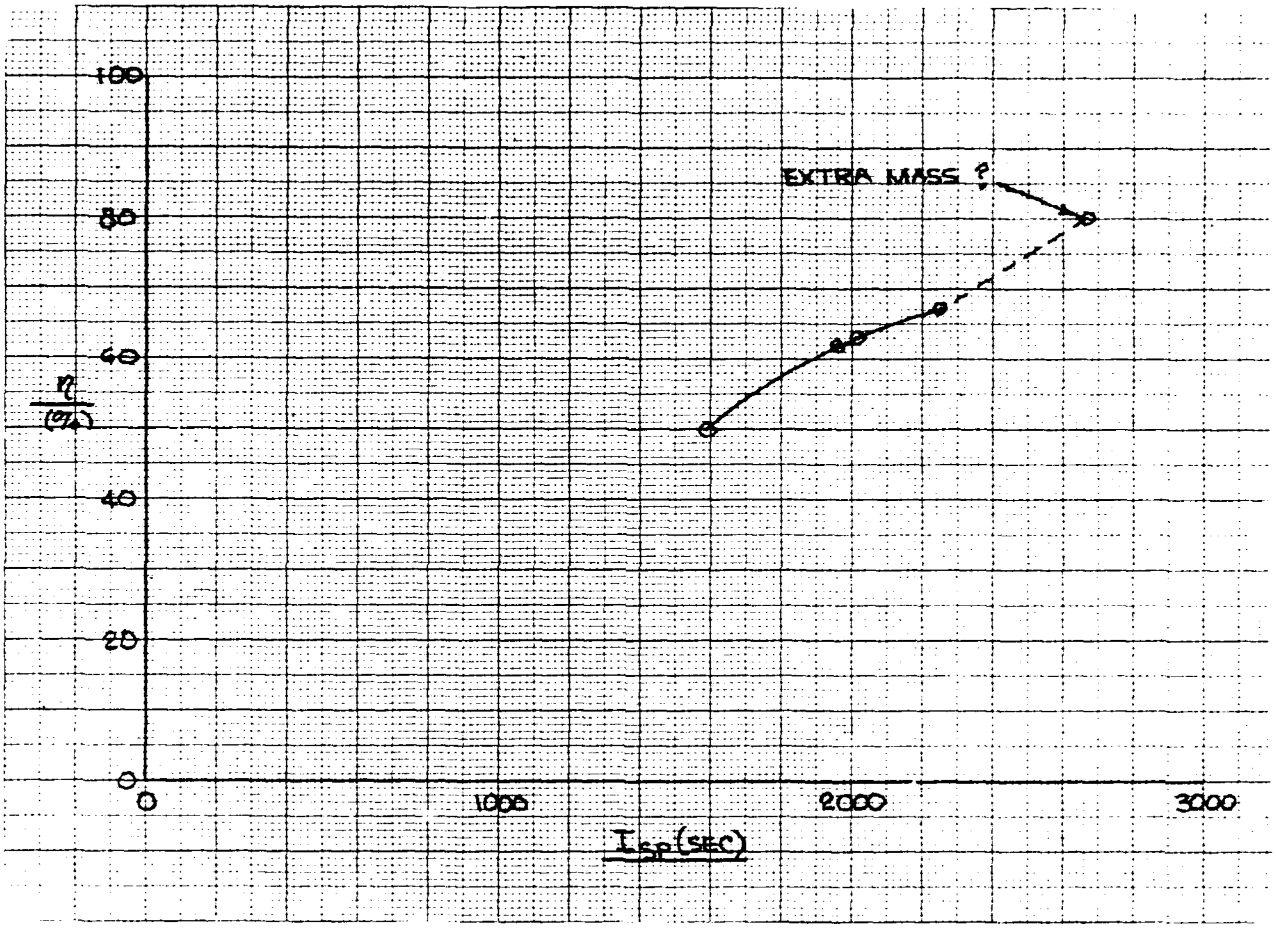

Figure 3. Thruster Efficiency versus Specific Impulse

by comparing Runs 34 and 35 which were identical except for the elimination of the obstruction in the latter run.

It should be mentioned that the first direct measurement of injected mass was made prior to Run 35 and was used for Runs 35 and 36. This calibration was used to calculate the mass for the previous runs, based on valve plenum pressure. This approach is not valid for most of the earlier runs, of course, but was regarded as a better estimate than the previous method (75% of the plenum mass). It is valid for Runs 28 through 34, since these were made with no changes in the valve conditions.

The five open circle data points in Figure 3 are based on direct measurements of injected argon propellant and the difference method of current density determination. The solid line, drawn through the four points from 1590 to 2250 seconds I_{sp} appears, at present, to be valid. The fifth point, at 2670 seconds I_{sp} seems high (both in efficiency and I_{sp}), suggesting the possibility of spurious mass addition in the accelerated plasma at the higher voltage of this test (24 kV).

The excellent repeatability shown in the impulse measurements for Runs 35, 37 and 38 under identical test conditions ($\pm$ 1%) is seen in the points clustered around 2000 seconds I_{sp} in Figure 3.

CONCLUSIONS AND RECOMMENDATIONS

The indication of a thruster efficiency on the order of 50 to 60% in the range of modest I_{sp}'s (1500 to 2500 seconds) of importance for near-Earth missions continues to be encouraging for the success of the pulsed inductive thruster concept. The direct measurement of injected propellant and elimination of spurious current density probe signals have strengthened the data base available by the probe technique. A direct, mechanical, measurement of impulse is needed to verify these results. The possibility of spurious mass addition to the accelerated plasma deserves a careful investigation.

REFERENCES

1. C. L. Dailey and R. H. Lovberg, "Pulsed Inductive Thruster Development (Advanced Electric Propulsion Technology - High Thrust)", AFRPL-TR-80-67, January, 1980.