

NASA/TM—1999-209449

PREPRINT

115
AIAA-98-3792



1N-20

Test Results of a 200W Class Hall Thruster

David T. Jacobson
Dynacs Engineering Company, Inc., Brook Park, Ohio

Robert S. Jankovsky
Glenn Research Center, Cleveland, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076



Test Results of a 200W Class Hall Thruster

David T. Jacobson
Dynacs Engineering Company, Inc., Brook Park, Ohio

Robert S. Jankovsky
Glenn Research Center, Cleveland, Ohio

Prepared for the
Joint Propulsion Conference
sponsored by the American Institute of Aeronautics and Astronautics
Cleveland, Ohio, July 13–15, 1998

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The authors would like to thank Mr. Michael Patterson of NASA GRC for the use of the laboratory cathode and his support in this effort. This piece of hardware was necessary to demonstrate the capabilities of the low power Hall thruster system. The authors would also like to thank Mr. Luis Pinero of NASA GRC and Glen Bowers of Gilcrest Electric for the design and fabrication of the BBPPU. A special thanks is extended to Patrick Barber of NASA's Test Installation Division for fabrication of the experimental hardware. His hard work and dedication is greatly appreciated.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

TEST RESULTS OF A 200W CLASS HALL THRUSTER

David T. Jacobson
Dynacs Engineering
Brook Park, Ohio 44142

Robert S. Jankovsky
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

The performance of a 200 W class Hall thruster was evaluated. Performance measurements were taken at power levels between 90 W and 250 W. At the nominal 200 W design point, the measured thrust was 11.3 mN, and the specific impulse was 1170 s excluding cathode flow in the calculation. A laboratory model 3 mm diameter hollow cathode was used for all testing. The engine was operated on laboratory power supplies in addition to a breadboard power processing unit fabricated from commercially available DC to DC converters.

INTRODUCTION

Over 70 Stationary Plasma Thrusters (SPT's) have been flown on Russian spacecraft since 1971.¹ Recently, there has been increasing U.S. Government and commercial interest in utilizing this technology on Western spacecraft due to the tremendous economic benefits and the maturation of Hall thruster systems. The Ballistic Missile Defense Organization (BMDO), through NASA, was at the forefront of efforts to demonstrate the benefits of Hall thruster technology with extensive testing of the SPT-100 beginning in 1993.² Since that time there has been an on-going research effort to evaluate Hall thruster technology.

NASA has recently placed an emphasis on smaller, lower cost, lower power spacecraft for space science missions. Propulsion system options for these small spacecraft are currently limited. Recent mission analysis indicated that a low-power Hall thruster system has mission enabling advantages over small spacecraft equipped with state-of-the-art (SOA) chemical systems.³ In an effort to demonstrate the

feasibility of a very low-power Hall system, NASA, through Atlantic Research Corporation, obtained a 200 W class Hall thruster built by the Research Institute of Applied Mechanics and Electroynamics of Moscow Aviation Institute

(RIAME). A performance evaluation of this engine was conducted and is presented in this report.

The main objective of this evaluation was to demonstrate the capabilities of very low-power laboratory model Hall thrusters. The second objective was to demonstrate the application of a low power 3 mm diameter hollow cathode being developed by NASA. The final objective was to illustrate the potential of building a low cost, low power Hall thruster system. The main activity associated with this objective was the design and fabrication of a breadboard power processing unit (BBPPU).

APPARATUS AND PROCEDURE

The Hall thruster used in this investigation was an SPT-30 obtained from the Research Institute of Applied Mechanics and Electroynamics of Moscow Aviation Institute (RIAME). The engine tested was a laboratory model thruster which would require additional development to achieve flight ready status. The SPT-30 derives its name from the outer diameter of the discharge chamber which is 30 mm. It utilizes separate coaxially wound inner and outer magnets, isolated from the discharge and each other, to generate the required magnetic field. The engine was designed to operate in the power range of 100-200 W and has an estimated lifetime

exceeding 600 hours. Performance testing of the engine was conducted by RIAME prior to this investigation. A photograph of the thruster installed on a thrust balance along with a 3 mm NASA hollow cathode is shown in Figure 1.

A 3 mm laboratory cathode based on the NASA Plasma Contactor design originally developed for the International Space Station (ISS) was used to operate the engine for the performance testing.⁴ Figure 2 is a photograph of this cathode. The cathode utilizes a low work function insert for electron emission. A resistance heater is used for pre-operation conditioning after exposure to atmosphere, and heating prior to ignition. The cathode was designed to operate with emission current between 0.5-1.5 A with xenon flow rates greater than 0.1 mg/s.

The thrust stand used for this test sequence was of an inverted pendulum type used previously for Hall thruster performance measurements.⁵ Recent modifications to the thrust stand electronic controls permitted thrust measurements to be performed using null rather than displacement method. The null type thrust stand is composed of three components including an electromagnetic driver, proportional, integral, differential, (PID) controller, and a Linear Variable Displacement Transformer (LVDT). The null method of measurement relies on current flow in a coil to generate an acceptable force via a magnetic field required to maintain a zero displacement. The current was measured using a shunt when the thruster was operating and output recorded using a strip chart recorder. Thrust calibrations were performed before, during and after testing. Three 0.48 g weights were applied using a stepping motor, providing a known coil current for a known force applied. Using this calibration data, the actual thrust produced by the engine was calculated. Reported thrust values have an estimated uncertainty of $\pm 2.0\%$.

Commercially available power supplies were used to operate the thruster and cathode for all performance measurements. Separate power supplies were used for the discharge, inner and outer magnets, cathode heater and keeper. A low voltage, high current keeper supply protected by a blocking diode was used in parallel with a high

voltage, low current ignitor supply for cathode ignition and operation. An output filter consisting of a 1.0 Ω ballast resistor in series with the anode and 100 μF capacitor between cathode and anode was used. Back to back 50 volt Zener diodes were used to protect the power supplies from an anomalous operating condition. An electrical schematic diagram of the power supply configuration is shown in Figure 3.

The engine was also successfully operated on a breadboard power processing unit (BBPPU) fabricated internally at NASA Glenn Research Center (GRC) from commercially available DC to DC converters. These commercial power modules operated from an input voltage of 21 to 32 Vdc provided regulated voltage, up to 285 Vdc, for the discharge and regulated currents for the inner and outer magnets and the cathode keeper and heater. These outputs can be individually adjusted through a wide range to optimize thruster operation. The power modules demonstrated an efficiency of 0.80 to 0.90, high power density, and functions including overcurrent and overvoltage protection.

Xenon flow was provided to the cathode and anode by a laboratory feed system which incorporated commercially available, National Institute of Standards and Technology (NIST) traceable flow controllers. Flow calibrations were performed before and after performance data was taken using a constant volume method. The uncertainty associated with the mass flow was estimated to be $\pm 1.0\%$. Commercially available research grade xenon with purity 99.999% was used. The feed system was helium leak checked prior to operation of the propulsion system.

All performance testing was conducted in the main volume of Vacuum Facility 8 at NASA GRC. The 1.5 m diameter and 5 m long chamber was equipped with a pumping train consisting of four 0.89 m oil diffusion pumps backed by two roughing pumps and a mechanical blower. The facility was capable of maintaining a background pressure of 1.0×10^{-5} Torr, measured with ion gauges calibrated on air and uncorrected for xenon, with the thruster operating at the highest mass flow rate.

Thruster performance was investigated over the power range 90 to 260 W. Thruster operation at a power level of greater than 200 W was limited to a period of 5 min as suggested by the manufacturer. Discharge current and voltage, cathode to ground voltage, and inner and outer magnet voltages were measured using calibrated digital multimeters. The discharge current and voltage were also recorded at each data point using a digital oscilloscope with storage capability. Data was collected at a fixed anode mass flow rate while varying discharge voltages between 100 and 250 V in 50 V increments.

The cathode was preheated prior to ignition at 9 A of heater current with a mass flow rate 0.5 mg/s. With the keeper supply set at 60 V, breakdown typically occurred within 2 minutes. The ignitor supply was only used on the first two starts, with ignition voltage of approximately 250 V. Successful cathode ignition was performed at lower mass flow rates of 0.3 and 0.2 mg/s later in the test sequence.

The discharge was initiated by turning on the discharge power supply with the current limit set at 1 A and the cathode operating on the keeper at 0.5 A with a flow rate of 0.1 mg/s. The inner and outer magnet current was set at 1 A and the discharge voltage was ramped up until breakdown occurred. The main discharge typically started at voltages between 35 and 50 V. Following initiation of the discharge, the discharge voltage was increased to the desired value, while incrementally increasing the inner and outer magnet current values to maintain stable operation. The starting procedure, implemented without modification, including the magnet current values, was suggested by RIAME. Because the thruster was stored for an extended period of time in an uncontrolled environment following delivery, the thruster was operated at low voltage in excess of one hour the first time the engine was operated. This allowed for outgassing of the hydroscopic insulators at an acceptably low rate.

RESULTS AND DISCUSSION

During this investigation, performance measurements were taken at power levels from 90 to 260 W. Data was collected at discharge voltages ranging from 100 to 250 V and discharge currents corresponding to anode mass

flow rates of 0.98, 0.75 and 0.61 mg/s. Data was taken at a nominal cathode mass flow rate of 0.1 mg/s. Although no single design point was specified by the manufacturer, discharge voltage and current values of 200 V and 1.0 A produced a power consistent with the maximum design power level. Performance values at a nominal operating point of 200 W indicate specific impulse of 1170 s with an efficiency of 0.32 excluding cathode flow, and a specific impulse of 1050 s with an efficiency of 0.29 including cathode flow. Specific impulses as high as 1290 s and efficiencies up to 0.29 were measured at the same power level, but at a correspondingly lower thrust. A complete table of the performance test results is provided as Table 1.

The relationship between the thrust produced by the SPT-30 and discharge power at three anode flow rates is shown in Figure 4. Because this particular engine was not designed with a magnetic system optimized with respect to power, power was calculated using only the discharge voltage and current and does not take into account the power dissipated in the magnets. The measured thrust produced was between 4.9 and 13.2 mN. Both the performance data taken in Vacuum Facility 8 at NASA GRC and that taken at the RIAME facility are included in this plot. Open symbols indicate data taken at NASA GRC and closed symbols indicating data taken at the RIAME facility. Two of the three data sets were taken at essentially the same anode mass flow, while the maximum flow rate at which data was taken was slightly higher in the test sequence performed at NASA GRC. All data series exhibit similar trends with the higher thrust produced at the highest mass flow rate. Scatter among points at essentially the same power can be attributed to differences in discharge current as a result of non-optimized magnet settings, and differences in discharge voltage values.

Specific impulse as a function of thruster power is shown in Figure 5 for three anode flow rates. Closed symbols indicate values calculated excluding cathode flow and open symbols cathode including cathode flow. Data were plotted for calculations performed with and without cathode flow to illustrate the effect of cathode flow on performance. This effect arises because propellant expended through the cathode is not accelerated and does not

contribute to the thrust produced by the engine. The higher specific impulse values occurred at the lowest anode mass flow rates, and in all cases, higher values were recorded at higher discharge voltages. A greater impact of cathode flow on performance is apparent at lower anode mass flow rates because cathode flow is a greater fraction of the total mass flow. The cathode flow fraction for this system ranged from 0.11 to 0.16. Further minituration of the cathode would significantly improve the performance of small Hall thrusters.

Thruster efficiency as a function of thruster power is shown in Figure 6 for three anode mass flow rates. Once again, data were plotted both with and without cathode flow and the symbol convention remains consistent. The efficiency values calculated including cathode flow were only 3-5% less than those calculated excluding cathode flow. This effect of cathode flow on performance was significantly reduced in comparison to data collected previously on other similar low power Hall systems which did not utilize a low flow cathode design.⁷

The current and voltage characteristics of the engine were recorded at each data point. Typical values of peak to peak discharge current oscillations ranged from 0.2 to 1.1 A. The current oscillations from the discharge power supply were minimal. Voltage oscillations were also minimal at each point.

In all cases, the procedure outlined in the previous section was used to start the discharge without any anomalous behavior, but difficulty sustaining a discharge while adjusting the magnet current was frequently experienced. As a result, the method of magnet optimization by minimization of the discharge current for a given discharge voltage and flow rate was not implemented.⁶ Instead, two magnet current setpoints were identified at which thruster stability was acceptable, and performance data were taken at those points. It is suspected that this behavior was partially a result of emissive characteristics of the cathode. A modification was made to the keeper orifice to increase the transparency of the plasma when initial difficulty was encountered starting the engine. Also, supplying a small amount of keeper current aided in maintaining a discharge; although, no performance data was recorded with the keeper

on. Engine operation with the cathode heater operating will be performed in future investigations to eliminate the possibility of the cathode extinguishing itself as a result of temperature.

The cathode orientation that was implemented was a result of initial difficulty encountered starting the engine. An initial attempt was made to operate the engine with the cathode positioned in a more traditional location with the axis of the cathode at a 45° angle to the exit plane of the thruster. The configuration of the keeper imposed geometric constraints which established the distance that the cathode was located from the discharge chamber. The center of the cathode orifice was 20 mm from the exit plane of the thruster and the 20 mm from the outer diameter of the discharge chamber. In this configuration, several unsuccessful attempts were made to initiate a discharge. The cathode was re-oriented such that the cathode was perpendicular to the thrust axis, and the distance from the orifice to the discharge chamber was minimized. No starting difficulties were encountered with the cathode in this configuration, and all performance testing was conducted with the cathode oriented in this fashion. Cathode position seems to have some impact on facilitating the initiation of the discharge. Further investigation would need to be conducted to determine the magnitude of the effect of cathode position on starting characteristics and performance to make any definitive conclusion.

CONCLUDING REMARKS

An investigation was conducted to evaluate the feasibility of using Hall thruster technology for very low power applications, using a low power laboratory model 200 W class Hall thruster. Data were collected at discharge voltages between 100 and 250 V without exceeding a power level of 200 W for a periods of more than 5 min. The thruster was capable of producing 11.3 mN of thrust at a nominal power level of 200 W. The specific impulse and efficiency values corresponding to that point were 1170 s and 0.32, respectively, excluding cathode flow.

All testing was conducted using a NASA laboratory model, low flow, 3 mm diameter

hollow cathode. Successful operation of the SPT-30 was demonstrated for emission current between 0.6 and 1.0 A. In some cases difficulty was encountered sustaining engine discharge. This may have been related to cathode position or temperature. The laboratory unit used for this performance test was not optimized with regard to keeper geometry or operation of a Hall thruster. Operation of the keeper or heater while performance measurements were being taken may have aided in sustaining a discharge. The benefit of a low flow hollow cathode on performance was demonstrated.

Operation of the engine on a breadboard power processing unit was demonstrated. To date, the BBPPU was used to operate the discharge up to voltages of 275 volts. Modifications are currently being implemented to allow for operation of the entire system without the combined use of laboratory power supplies.

REFERENCES

1. Clauss, C.W., Tilley, D.L., and Barnhart, D.A., "Benefits of Low-Power Stationary Plasma Thruster Propulsion For Small Satellites." Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites, Utah, Sept. 1995
2. Sankovic, J.M., Hamley, J.A., and Haag, T.W., "Performance Evaluation of the Russian SPT-100 Thruster at NASA LeRC." IEPC-93-094, Sept. 1993.
3. Oleson, S., "Electric Propulsion For Low Earth Orbit Communication Satellites." IEPC-97-148, August, 1997.
4. Patterson, M.J., Hamley, J.A., Sarver-Verhey, T.R., Soulas, G.C., Parkes, J.E., Ohlinger, W.L., Schaffner, M.S., and Nelson, A., "Plasma Contactor Technology for Space Station Freedom." AIAA-93-2228, June 1993.
5. Hagg, T.W., and Osborn, M., "RHETT/EPDM Performance Characterization." IEPC-97-107, August 1997.
6. Sankovic, J.M., Haag, T.W., and Manzella, D.H., "Operating Characteristics of the Russian D-55 Thruster with Anode Layer." AIAA-94-3011, June 1994.
7. Manzella, D.H., Oleson, S., Sankovic, J.M., Haag, T.W., Semenkin, A., and Kim, V., "Evaluation of Low Power Hall Thruster Propulsion." AIAA-96-2736, July, 1996.

Table 1. Performance values collected for testing of SPT-30 Hall thruster.

Discharge Voltage	Discharge Current	Anode Flow	Cathode Flow	Power	Thrust	Specific Impulse	Efficiency	Specific Impulse*	Efficiency*
V	A	mg/s	mg/s	W	mN	s		s	
200	1.01	0.98	0.11	202.0	11.3	1050	0.29	1170	0.32
150	1.02	0.98	0.11	153.0	8.8	823	0.23	914	0.26
100	0.99	0.98	0.10	99.0	5.6	521	0.14	576	0.16
250	1.03	0.98	0.11	257.5	13.2	1230	0.31	1370	0.34
150	1.02	0.98	0.11	153.0	8.8	822	0.23	915	0.26
150	0.79	0.75	0.10	118.5	6.9	818	0.23	931	0.27
200	0.78	0.75	0.10	156.0	8.3	986	0.26	1120	0.29
250	0.82	0.75	0.10	205.0	9.5	1130	0.26	1290	0.29
150	0.75	0.75	0.10	112.5	6.5	775	0.22	882	0.25
150	0.60	0.61	0.10	90.0	4.9	700	0.19	819	0.22
200	0.60	0.61	0.10	120.0	6.2	874	0.22	1020	0.26
250	0.63	0.61	0.10	156.3	7.0	1000	0.22	1170	0.26

* denotes efficiency and specific impulse values calculated excluding cathode flow

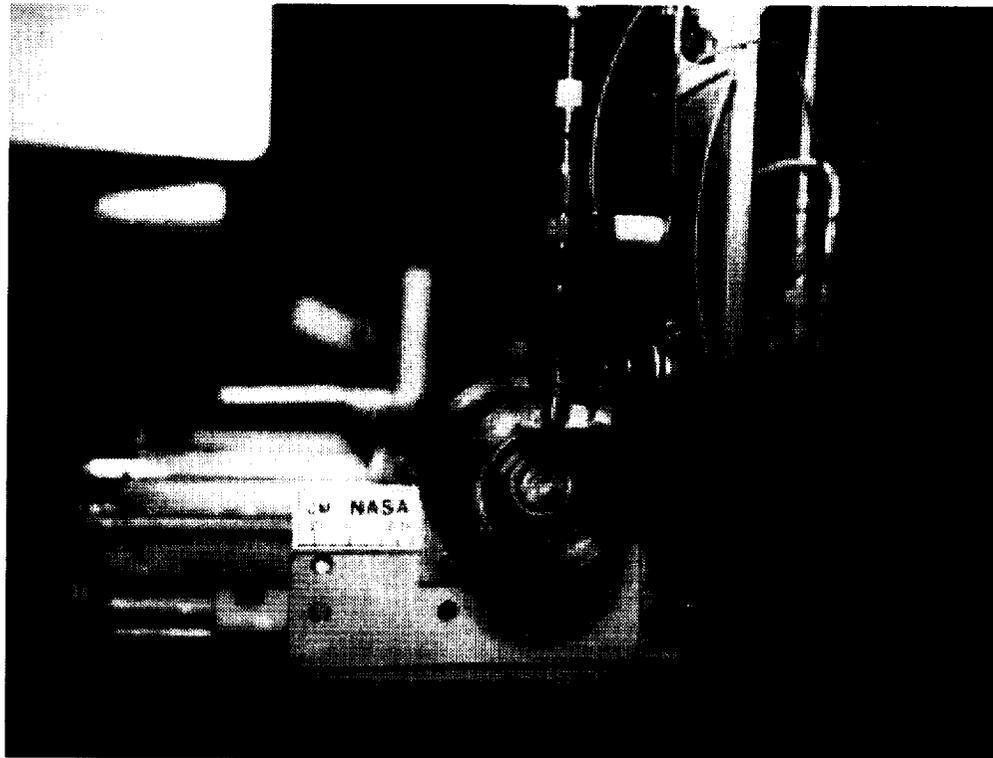


Figure 1. SPT-30 on thrust stand in vacuum facility 8 at NASA Glenn Research Center.

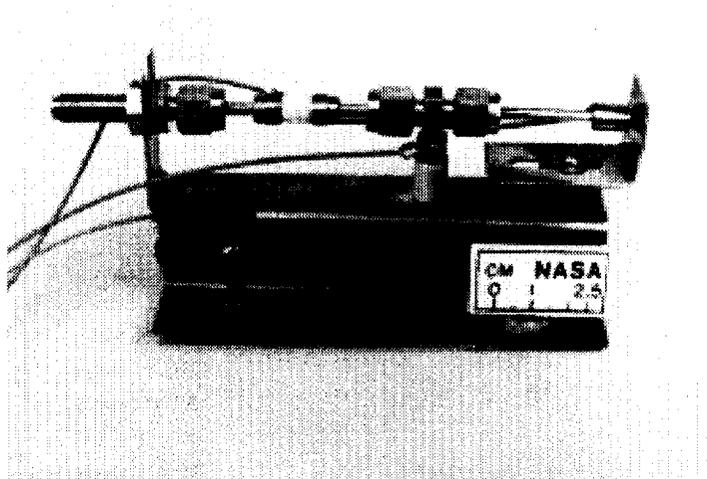


Figure 2. NASA Laboratory Model, low-flow cathode.

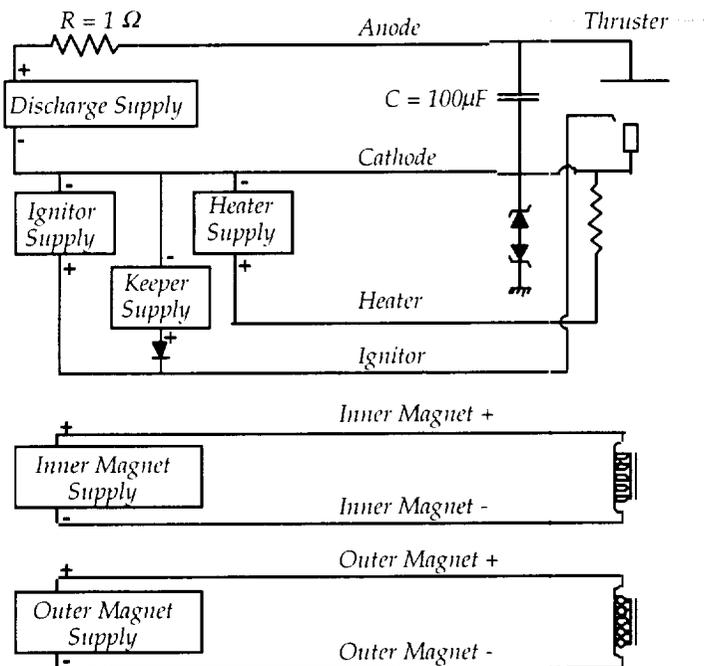
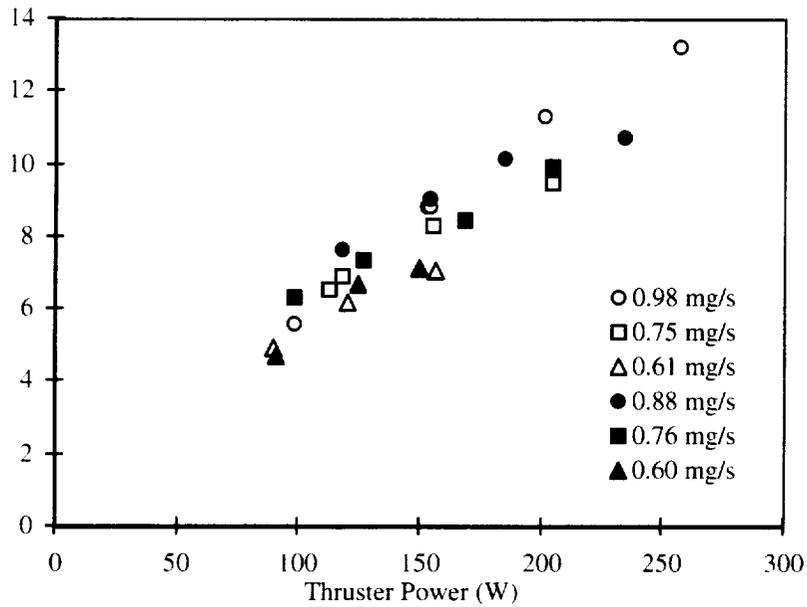
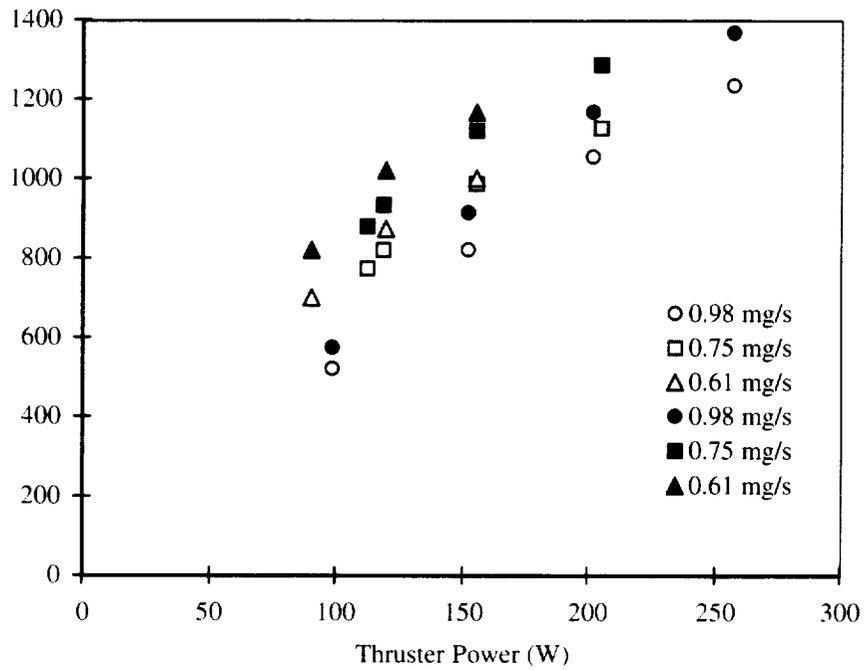


Figure 3. Electrical Schematic diagram.



Open Symbol-NASA GRC Data
 Closed Symbol-RIAME Data

Figure 4. Comparison of performance data taken at NASA GRC and RIAME.



Open Symbols-including cathode flow
 Closed Symbol-excluding cathode flow

Figure 5. Specific Impulse verse thruster power both with and without cathode flow.

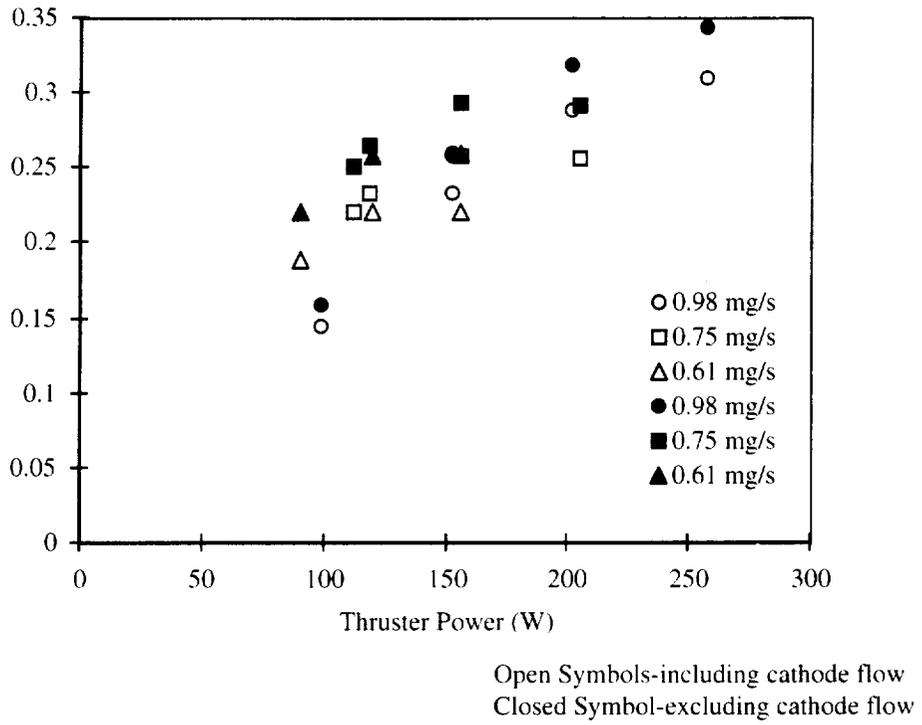


Figure 6. Efficiency verse thruster power both with and without cathode flow.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1999	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE Test Results of a 200W Class Hall Thruster			5. FUNDING NUMBERS WU-632-1B-1B-00	
6. AUTHOR(S) David T. Jacobson and Robert S. Jankovsky				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-11941	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-1999-209449 AIAA-98-3792	
11. SUPPLEMENTARY NOTES Prepared for the Joint Propulsion Conference sponsored by the American Institute of Aeronautics and Astronautics, Cleveland, Ohio, July 13-15, 1998. David T. Jacobson, Dynacs Engineering Company, Inc., Brook Park, Ohio 44142, and Robert S. Jankovsky, NASA Glenn Research Center. Responsible person, Robert S. Jankovsky, organization code 5430. (216) 977-7515.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 20 This publication is available from the NASA Center for AeroSpace Information. (301) 621-0390.			12b. DISTRIBUTION CODE Distribution: Nonstandard	
13. ABSTRACT (Maximum 200 words) The performance of a 200 W class Hall thruster was evaluated. Performance measurements were taken at power levels between 90 W and 250 W. At the nominal 200 W design point, the measured thrust was 11.3 mN, and the specific impulse was 1170 s excluding cathode flow in the calculation. A laboratory model 3 mm diameter hollow cathode was used for all testing. The engine was operated on laboratory power supplies in addition to a breadboard power processing unit fabricated from commercially available DC to DC converters.				
14. SUBJECT TERMS Hall thruster			15. NUMBER OF PAGES 15	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	