Plasma Thruster Development

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FOREWORD

This final technical report, entitled "Plasma Thruster Development," presents the results of an in-house study performed under JON 305800C4 by the Air Force Research Laboratory, Propulsion Directorate (AFRL/PRSS), Edwards AFB CA. The Project Managers for the Air Force Research Laboratory were Dennis Tilley, J. Chris Andrews, Greg Spanjers, and Bill Hargus.

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Research Objectives

To investigate and resolve technical issues associated with electric propulsion thrusters; specifically performance and spacecraft integration issues. Thrusters examined include magneto-plasma-dynamic (MPD) thrusters, arcjets, Hall thrusters, and pulsed plasma thrusters (PPT).

- Identify methods to significantly increase MPD efficiencies
- Characterize and test laboratory arcjets in support of flight experiments
- Demonstrate significant gains in impulse to wet mass ratios for Hall thrusters
- Develop and test advanced PPT design concepts

Summary of Results

MPD:

- A series of tests identified the mechanism responsible for the high anode fall within an MPD thruster. Measurements included magnetic field, current density, electron temperature, electron number density, plasma potential, and anode fall voltage. This effort resulted in one of the first non-trivial, successful comparisons between numerically predicted and experimentally determined plasma properties inside an MPD thruster.
- An effort was mounted to experimentally determine operating conditions where plasma microturbulance affects efficiency of MPD operation. Locations inside the thruster and in the plume were examined for microinstabilities. Mean plasma properties also measured during these tests were used to measure electrical conductivity incorporating the effects of the observed microinstabilities.

Arcjet:

- Arcjet ignition tests in support of ESEX (Electric Space Experiment) identified propellant breakdown mechanisms which led to the construction of an arcjet ignition model. This research provided the first fundamental understanding of the propellant process in the arcjet. Experiments performed at AFRL, along with this new understanding of the propellant breakdown process, were used as the basis for the redesign of the ESEX start circuit.
- Paper AIAA-93-1901 "An Investigation of the Breakdown Voltage Characteristics of a 30 kW Class Ammonia Arcjet" at the 29th Joint Propulsion Conference received "Best Paper in Electric Propulsion Award."
- Internal diagnostics of the expansion process within a 30 kW class arcjet nozzle were performed using emission spectroscopy. These tests measured temperatures of various heavy particles (H, N, NH), electron temperature and number density, as well as cathode temperatures from continuum emission.
- Several new arcjet diagnostics, current modulation velocimetry and pulse electron beam fluorescence, were developed at AFRL in cooperation with the University of Southern California. These diagnostics allow for the determination of the mean exit velocity and density measurements of an arcjet flow.
- The first use of two photon laser induced fluorescence in an arcjet plume was performed at AFRL. In this study, ground state hydrogen atoms were detected with high spatial resolution near the exit plane. Number density, axial and radial velocities, and translational temperature distributions were also obtained.

• Laboratory tests of a 30 kW class ammonia arcjet were conducted to investigate the electromagnetic environment in the range of DC to 10 GHz using antennas intended to characterize electric and magnetic fields. These tests showed that the electromagnetic fields produced by an arcjet operating as part of a satellite propulsion system are lower than predicted.
• An effort was made to improve the performance of subkilowatt arcjets in the power range of 300-600 W. In support of this effort, thrust measurements, two color optical pyrometry, and thermocouples were used to characterize several nozzle geometry's.
• Paper AIAA-96-3185 "Comparisons of Hydrogen Atom Measurements in an Arcjet Plume with DSMC Predictions" awarded "Best Paper for the Conference".

Hall Thruster:
• The MSTI (Miniaturized Space Technology Integration) program was supported in an effort that examined the integration of Russian Hall thruster technology on to the MSTI platform.
• Analytical methods were combined with data from current Hall thruster technology to formulate a model to predict the performance requirements for several orbit transfer missions. The study determined that reusable electric orbit transfer vehicles can offer significant payload mass gains over chemical systems.
• A high speed reciprocating probe system was constructed and used to investigate the perturbations of electrostatic on Hall thruster operations and on the measurement of local plasma parameters. Experiments indicate that within the interior of the thruster, significant probe material ablation occurred and severe perturbations to thruster operation and measurements could be avoided by use of a high speed probe, which minimized probe residence time to less than 500 ms.
• AFRL in cooperation with the University of Michigan developed a 5 kW class Hall thruster. This thruster was developed to investigate, with a variety of diagnostics, a thruster that operates at conditions comparable to similar thrusters under commercial development.

PPT:
• Measurements were made of the solid propellant conversion process with the intent of better understanding of the propellant gasification process. Increased understanding of the propellant conversion process will lead to the design of PPTs with significantly improved propellant efficiencies.
• Propellant inefficiency resulting from the ejection of propellant material in particulate form was characterized. Exhaust deposits were collected and analyzed using scanning electron microscopy, energy dispersion x-ray analysis, and microscopic imaging. Estimates of propellant entrained in this mode show that particulates account for up 40% of the utilized propellant mass while contributing less than 1% of the thrust, indicating that methods of reducing this loss mechanism would result in a significant improvement in PPT thrust efficiency.
• A correlation was established between decreased propellant temperature and increased propellant efficiency. A 25% gain in thrust efficiency was demonstrated by decreasing the propellant bar temperature by approximately 90°C.
• A study was initiated to measure and analyze the optical emission spectra of the plasma produced by Teflon propellant PPT. Survey spectra from 350 to 750 nm were recorded and indicate that no new species are formed as the discharge energy is increased. Relative line ratios did not vary also indicating that bulk properties of the discharge plasma are not affected by the

energy dissipated in each discharge. However, time resolved measurements showed that the magnitude of emission intensity closely followed PPT current and discharge energy.

Publications: (Chronological Order)

Bromaghim, D. R., Measurement of Magnetic Fields Produced by a 30 kWe Class Arcjet Power Conditioning Unit, PL-TR-92-3049, OL-AC Phillips Laboratory, EAFB, CA, January 1993.

Tilley, D. L., McFall, K. A., Castillo, S. C., and Andrews, J. C. "An Investigation of the Breakdown Voltage Characteristics of a 30Kw Class Ammonia Arcjet", AIAA 93-1901, 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Monterey, CA, June 28-30, 1993.

Johnson, L. K., Lundquist, M., Rivera, A., Sanks, T. M., Sutton, A., and Bromaghim, D. R. "Frequency-Domain Electromagnetic Characteristics of a 26kW Ammonia Arcjet", AIAA 93-2393, 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Monterey, CA, June 28-30, 1993.

Pobst, J. A., Schilling, J. H., and Spores, R. A. "Time Resolved Measurements of a 1kW Arcjet Plumes using Current Modulation Velocimetry and Triple Langmuir Probes", IEPC-93-128, 23rd International Electric Propulsion Conference, Seattle, WA, September 13-16, 1993.

Barnhart, D. A., McCombe, J. M., and Tilley, D. L., "Electric Propulsion Integration Activities on MSTI Spacecraft", IEPC-93-011, 23rd International Electric Propulsion Conference, Seattle, WA, September 13-16, 1993.

Bowmen, E., and Tilley, D. L., "Microinstabilities in High-Power MPD Systems: Preliminary Diagnostics", IEPC-93-125, 23rd International Electric Propulsion Conference, Seattle, WA, September 13-16, 1993.

Tilley, D. L., "Propellant Breakdown Mechanisms in an Arcjet", IEPC-93-050, 23rd International Electric Propulsion Conference, Seattle, WA, September 13-16, 1993.

Burton, R. L., DelMedico, S. G., and Andrews, J. C., "Application of a Quadruple Probe Technique to MPD Thruster Plume Measurements", *AIAA Journal of Propulsion and Power*, Vol. 9, No. 5, 1993, pp. 771-777.

Johnson, L. K., Lundquist, M., Rivera, A., Sanks, T. M., Sutton, A., and Bromaghim, D. R., "Frequency-Domain Electromagnetic Characteristics of a 26kW Ammonia Arcjet", ATR-93 (8309)-1, The Aerospace Corporation, El Segundo, CA, 1993.

Tilley, D. L., Castillo, S., Jolly, M. S., Niewood, E., and Martinez-Sanchez, M., "A Comparison of Theory and Measurements in the Anode Region of a Self-Field Cylindrical MPD Thruster", AIAA 94-3337, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, June 27-29, 1994.

Hargus, W. Jr., Micci, M., and Spores, R. A., "Interior Spectroscopic Investigation of the Propellant Energy Modes in an Arcjet Nozzle", AIAA 94-3302, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, June 27-29, 1994.

Pobst, J. A., Shilling, J. H., Lutfy, F. M., Erwin, D. A., and Spores, R. A., "Arcjet Diagnostics using Current Modulation Velocimetry and Pulsed Electron Beam Fluorescence", AIAA 94-2742, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, June 27-29, 1994.

Spores, R. A., Hargus, W. A. Jr., Pobst, J. A., Shilling, J. H., Lutfy, F. M., and Erwin, D. A., "Arcjet Diagnostics for Measuring Velocity, Density and Temperature", AIAA 94-2464, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN, June 27-29, 1994.

Pobst, J. A., Wysong, I. J., and Spores, R. A., "Laser Induced Fluorescence of Ground State Hydrogen Atoms in a Arcjet Plume", AIAA 95-1973, 26th AIAA Plasmadynamics and Lasers Conference. San Diego, CA, June 19-22, 1995.

Clauss, C. W., Tilley, D. L., and Barnhart, D. A., "Benefits of Low-Power Stationary Plasma Thruster Propulsion For Small Satellites", 9th AIAA/Utah State University Conference on Small Satellites, September 18-21,1995.

Patel, B. T., Martinez-Sanchez, M., Ricker, G. R., Tilley, D., Barnhart, D., Alexander, H., Myers, R., Pencil, E., Horvat, G., and Samella, J., "Electric Propulsion for an Interplanetary Astrophysics Mission", IEPC-95-239, 24th International Electric Propulsion Conference, Moscow, Russia, September 19-23, 1995.

Barnhart, D., Wojnar, R., Tilley, D., and Spores, R. A., "The Case For Small Spacecraft: An Integrated Perspective on Electric Propulsion", IEPC-95-148, 24th International Electric Propulsion Conference, Moscow, Russia, September 19-23, 1995.

Pobst, J. A., Wysong, I. J., and Spores, R. A., "Laser Induced Fluorescence of Ground State Hydrogen Atoms in a Arcjet Plume", IEPC-95-28, 24th International Electric Propulsion Conference, Moscow, Russia, September 19-23, 1995.

McFall, K. A., Tilley, D., and Gulczinski, F. S., III, "Low Power Arcjet Performance Evaluation", IEPC-95-18, 24th International Electric Propulsion Conference, Moscow, Russia, September 19-23, 1995.

Tilley, D. L., Choueiri, E. Y., Kelley, A. J., and Jahn, R. G., "Microinstabilities in a 10 kW Self-Field Magnetoplasmadynamic Thruster", *AIAA Journal of Propulsion and Power*, Vol. 12, No. 2,1996, pp. 381-389.

Johnson, L. K., Rivera, A., Lundquist, M., Sanks, T. M., Sutton, A., and Bromaghim, D. R., "Frequency-Domain Electromagnetic Characteristics of a 26-Kilowatt Ammonia Arcjet", *AIAA Journal of Spacecraft and Rockets*, Vol. 33, No. 1,1996, pp. 137-143.

Berns, D. H., Storm, P. V., Hargus, W. A., Jr., Cappelli, M. A., McFall, K. A., and Spores, R. A., "Plasma and Cathode Emission from a High Power Hydrogen Arcjet Thruster", AIAA 96-2703, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Lake Buena Vista, FL, July 1-3, 1996.

Wysong, I. J., Pobst, J. A., and Boyd, I. D., "Comparisons of Hydrogen Atom Measurements in an Arcjet Plume with DSMC Predictions", AIAA 96-3185, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Lake Buena Vista, FL, July 1-3, 1996.

Gulczinski, F. S., III and Spores, R. A., "Analysis of Hall-Effect Thrusters and Ion Engines for Orbit Transfer Missions", AIAA 96-2973, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Lake Buena Vista, FL, July 1-3, 1996.

Tilley, D. L., and Spores, R. A., "Life Extension Strategies for Space Shuttle-Deployed Small Satellites Using a Pulsed Plasma Thruster", AIAA 96-2730, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Lake Buena Vista, FL, July 1-3, 1996.

Spanjers, G. G., McFall, K. A., Gulczinski, F. S., III and Spores, R. A., "Investigation of Propellant Inefficiencies in a Pulsed Plasma Thruster", AIAA 96-2723, 32nd AIAA/ASME/ SAE/ASEE Joint Propulsion Conference & Exhibit. Lake Buena Vista, FL, July 1-3, 1996.

Pobst, J. A., Spores, R. A., Shilling, J. H., and Erwin, D. A., "Fluctuation of Arcjet Plume Properties", *AIAA Journal of Propulsion and Power*, Vol.12, No. 6, 1996, pp. 1107-1113.

Spanjers, G. G., Lotspeich, J. S., McFall, K. A., and Spores, R. A., "Propellant Inefficiency Due to Particulate in a Pulsed Plasma Thruster", Space Technology & Applications Forum (STAF-97), Albuquerque, NM, January 26-30, 1997.

Markusic, T. E., and Spores, R. A., "Spectroscopic Emission Measurements of a Pulsed Plasma Thruster Plume", AIAA 97-2924, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. Seattle, WA, July 6-9, 1997.

Spanjers, G. G., Malak, J. B., Leiweke, R. J., and Spores, R. A., "The Effect of Propellant Temperature on Efficiency in a Pulsed Plasma Thruster", AIAA 97-2924, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Seattle, WA, July 6-9, 1997.

Haas, J. M., Gulczinski, F. S., III, Gallimore, A. D., Spanjers, G. G., and Spores, R. A., "Performance Characteristics of a 5kW Laboratory Hall Thruster", AIAA 98-3503, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland, OH, July 13-15, 1998.

Haas, J. M., Spanjers, G. G., McFall, K., and Spores, R. A., "An Investigation of Electrostatic Perturbations on the Operational Characteristics of a Hall Thruster and on the Measurement of Local Plasma Parameters", AIAA 98-3656, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland, OH, July 13-15, 1998.

Spanjers, G. G., Lotspiech, J. S., McFall, K. A., and Spores, R. A., "Propellant Losses Because of Particulate Emission in a Pulsed Plasma Thruster", *AIAA Journal of Propulsion and Power*, Vol. 14, No. 4, 1998, pp. 554-559.

Schilling, J. H., Spores, R. A., and Spanjers, G. G., "Micropropulsion Options for the TechSat21 Space Based Radar Flight", submitted to *AIAA Journal of Propulsion and Power*.

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