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NASA's 2004 Hall Thruster Program

David T. Jacobson and David H. Manzella
Glenn Research Center, Cleveland, Ohio

Richard R. Hofer and Peter Y. Peterson
QSS Group, Inc., Cleveland, Ohio

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David T. Jacobson and David H. Manzella
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Richard R. Hofer and Peter Y. Peterson
QSS Group, Inc.
Cleveland, Ohio 44135

An overview of NASA's Hall thruster research and development tasks conducted during fiscal year 2004 is presented. These tasks focus on: raising the technology readiness level of high power Hall thrusters, developing a moderate-power/moderate specific impulse Hall thruster, demonstrating high-power/high specific impulse Hall thruster operation, and addressing the fundamental technical challenges of emerging Hall thruster concepts. Programmatic background information, technical accomplishments and out year plans for each program element performed under the sponsorship of the In-Space Transportation Program, Project Prometheus and the Energetics Project are provided.

I. Introduction

NASA's 2004 Hall thruster program consisted of research and development tasks performed in support of the Energetics Project, the In-Space Transportation Program (ISTP) and Project Prometheus. The Energetics Project, an element of the Aerospace Technology Enterprise's Mission and Science Measurement Technology (MSM) theme and funded by the Enabling Concepts and Technology Program, addresses the fundamental technical challenges of low technology readiness level[1] (TRL) Hall thruster concepts. The FY04 Energetics sponsored Hall thruster tasks addressed the technical challenges of advancing the existing Hall thruster technology to higher power levels, higher specific impulse, higher efficiency and longer lifetimes. The ISTP, managed by NASA Marshall Space Flight Center, develops advanced propulsion technologies to replace conventional propulsion systems for space science missions within and beyond Earth orbit. In support of this program, NASA Glenn Research Center (GRC) developed a 6-8 kW Hall thruster and redesigned a moderate specific impulse, 50 kW device based on the existing NASA-457M Hall thruster. Directed research pertaining to high-power, high specific impulse Hall thrusters was conducted under the sponsorship of Project Prometheus. This effort has culminated in the design and fabrication of the NASA-400M Hall thruster, designed for 50 kW operation at specific impulses greater than 4500 seconds. A description of NASA GRC's program year 2004 accomplishments in the area of Hall thruster propulsion is presented.

II. In-Space Transportation Program-Directed Hall Thruster Development Task

A. Programmatic Background

The FY04 development of an engineering model, 50 kW Hall thruster builds on 7 years of high-power Hall thruster research. The Advanced Space Transportation Program (ASTP) sponsorship of high-power Hall thruster development began in 1997 with the award of a 10 kW Hall thruster contract to TRW, Space Power Inc. and the Keldysh Research Center. Under this contract, the T-220 Hall thruster was delivered to NASA GRC and a performance investigation was conducted in 1998.[2] The program concluded in FY00 following a 1000 hour erosion characterization.[3] Sponsorship of high-power Hall thruster development continued with the establishment of the ISTP funded by the Office of Space Science. In 2001, Aerojet Redmond Rocket Center was competitively selected to design a 50 kW Hall thruster as a complementary effort to NASA GRC's in-house development of the NASA-457M thruster. A contract option for thruster fabrication was exercised and the thruster was delivering to NASA GRC in 2002 and tested in 2003. In FY04, the high-power Hall thruster development funded by the ISTP was refocused on the GRC developed, NASA-457M, 50 kW Hall thruster.

The objective of the FY04, ISTP Directed Hall Thruster Development Task was to advance the TRL of high-power Hall technology from TRL 3 to TRL 4/5. The fidelity of the existing, laboratory model NASA-457M Hall thruster was improved by addressing thermal, mechanical and structural issues. The critical features of the laboratory model thruster were incorporated into a NASA-457M version 2 (V2) that provides an evolutionary path to a flight type device. A Hall thruster specific, high-emission current hollow cathode was also designed. A description of the NASA-457M V2 development tasks follows.

B. FY04 Technical Accomplishments

During FY04 an engineering model, 50 kW Hall thruster (NASA-457M V2) was designed. This thruster was designed with the same channel diameter (457 mm), width and depth as the laboratory model thruster (NASA-457M V1). The magnetic circuit was designed for improved performance and reduced mass compared to the version 1 thruster. The magnetic circuit retained a plasma lens topography[4,5] with improved performance and symmetry. The centerline radial magnetic field strength was increased by nearly 20% for the same number of Amp-turns. Improvements in the magnetic circuit performance were achieved while the mass of the magnetic circuit was reduced by 18% compared to the laboratory model thruster.

The NASA-457M V2 mechanical design eliminated deficiencies with respect to anode mounting and electrical isolation, concentricity, and thermally induced mechanical interferences. A representative spacecraft mounting interface was designed. The suitability of the mechanical design was assessed using computer aided design techniques. A solid model of the thruster was generated and finite element thermal and mechanical analyses were performed. A dynamic mechanical simulation was performed to assess vibration tolerance and identify fundamental frequencies. The solid model was also used to perform a static deflection and stress analysis. Application of representative launch loads to the thruster interface revealed excessive structural deformation, which was subsequently eliminated through modification of the mechanical design. A 3-D thermal model, which included thermal contact conductance and radiation elements, was generated from the structural finite element model (FEM). The analytical results were compared to the version 1 thruster experimental data and adjustments made to the boundary condition application. The predicted temperatures were applied to the structural FEM and used to predict thermal displacements and corresponding stresses. Mechanical design changes were incorporated as a result of this analysis. A solid model rendering of the final NASA-457M V2 design is shown if Figure 1. The thruster fabrication was initiated in May 2004 and functional and performance testing will be completed by the end of the CY04.

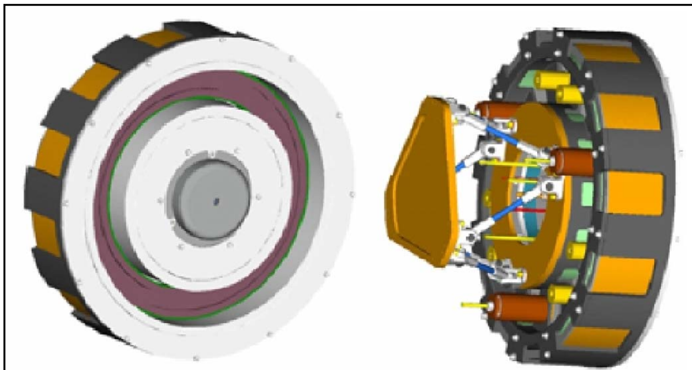

Figure 1. A solid model rendering of NASA-457M V2.

A high-emission current hollow cathode design and evaluation task was also conducted as a part of this effort. The objective of this task was to develop a simple, modular device to facilitate characterization and design refinement of 100 Ampere emission current hollow cathode technology. The cathode was also specifically designed for the NASA-457M V2 application while incorporating the design heritage of the International Space Station plasma contactor[6] and ion thruster hollow cathode technology[7]. Parameters including cathode orifice size, insert diameter, cathode to keeper spacing, propellant flow rate and propellant type were considered in the design process. Multiple cathode tube subassemblies were fabricated to experimentally determine the cathode geometry required for the desired emitter temperature needed to ensure required lifetimes. Selection of the final cathode geometry will be based on these experimental results and the final configuration integrated for testing with the NASA-457M V2. A solid model rendering of the NASA-457M V2 hollow cathode design is shown if Figure 2.

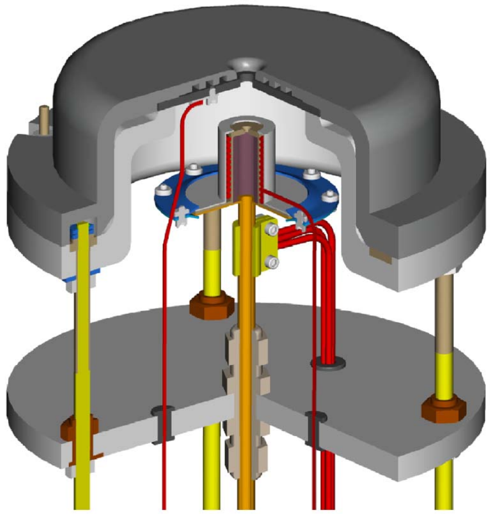

Figure 2. The 100 Ampere emission current hollow cathode.

C. Out-Year Plan

The ISTP investment in high-power Hall thruster technology will not continue beyond FY04. High-power Hall thruster technology is more applicable to the missions of interest to programs funded under NASA's recently established Exploration Systems Enterprise. ISTP sponsored electric propulsion activities will focus on lower power technologies such as the on-going High Voltage Hall Accelerator (HIVHAC) Development Program.

III. In-Space Transportation Program High Voltage Hall Accelerator (HIVHAC) Development Program

A. Programmatic Background

The HIVHAC Development Program was competitively selected under NASA's In-Space Propulsion Technologies Cycle 2 NASA Research Announcement (NRA) solicitation. The Cycle 2 NRA solicited for "kW Solar Electric Propulsion System technology" which offered mission benefit compared to the 4000 second NEXT ion system for an interplanetary robotic exploration deep space design reference mission (DSDRM). GRC performed mission analysis that compared Hall thruster technology to the NEXT ion thruster system for Neptune and Saturn DSDRM's. This analysis indicated that a Hall propulsion system, used for the Earth escape and interplanetary transfer, offers a trip time reduction or increase in payload for these space science DSDRM's. Based on this analysis, GRC proposed to develop a 6-8 kW Hall thruster that operated at specific impulses ranging from 2200-2800 seconds. In May 2003 the HIVHAC Development Program was selected for award. This NASA GRC led effort is being performed with collaboration with Aerojet Redmond Rocket Center, Jet Propulsion Laboratory (JPL) and the University of Michigan.

B. FY04 Technical Accomplishments

A Hall thruster that operates at discharge voltages more than 2 times that of SOA devices was designed to achieve the HIVHAC specific impulse objective. (Current SOA Hall thrusters operate at 300 Volts.) All of the HIVHAC performance objectives and thruster characteristics are shown in Table 1.

Table 1. Performance objectives and thruster characteristics of the HIVHAC Hall thruster.

Thruster Characteristic	Value
Total specific impulse:	2200-2800 s
Input power	6-8 kW
Propellant	xenon
Total thruster efficiency	>62%
Thrust	430 mN
Propellant throughput	> 400 kg
Specific mass	1.3 kg/kW
Discharge voltage	500-700 V
Current density:	comparable to SOA thrusters
Power density	2x SOA thrusters
Operational lifetime	6000 hrs @ 8 kW, 8000 hrs @ 6kW

The Cycle 2 NRA solicited demonstrated technologies (TRL 3) and required that the technology be advanced by one full technology readiness level over the project duration. The HIVHAC performance had previously been demonstrated with the NASA-173 V2 Hall thruster; as a result, the HIVHAC thruster was based on this existing laboratory model NASA thruster. The TRL of high specific impulse Hall thrusters will be raised to TRL 4 by developing a prototype thruster, which could be developed to TRL 9.

NASA GRC performed the design of the HIVHAC thruster geometry and magnetic circuit. An outer diameter of 170 mm was selected to provide the desired current and power density. The channel width was selected to be the same as the NASA-173M V2 to maintain design similarity. The magnetic field topography was also preserved and the mass of the magnetic circuit was reduced by 30% compared to the NASA-173M V2 (6% due to size reduction). The thruster dimensions and magnetic circuit configuration were provided to Aerojet Redmond Rocket center where the remaining engineering and mechanical design of HIVHAC thruster was completed. A photograph of the NASA-173M V2 Hall thruster and a rendering of the completed HIVHAC thruster is shown in Figure 3.

JPL used an existing computer code[8] to simulate the evolution of the plasma of a HIVHAC thruster, including the fluxes and energies of the ions colliding with the walls of the thruster acceleration channel. These data were used together with sputtering yields for BN-Xe, compiled from available literature[9-12], to estimate the erosion rate of the insulating walls. A peak erosion rate of approximately 1.6 microns/hour was obtained for nominal HIVHAC operation parameters (15 mg/s Xe mass flow rate, 600 V discharge voltage).

C. Out-Year Plan

NASA GRC performance testing, University of Michigan plume characterization and additional JPL lifetime modeling was scheduled to occur during FY05. As a result of mission analysis conducted in support of an FY04 ISTP technology reassessment, the design point of the HIVHAC thruster is being reevaluated to maximize relevance to Code S missions. These reassessment activities may affect the future of the current HIVHAC program.

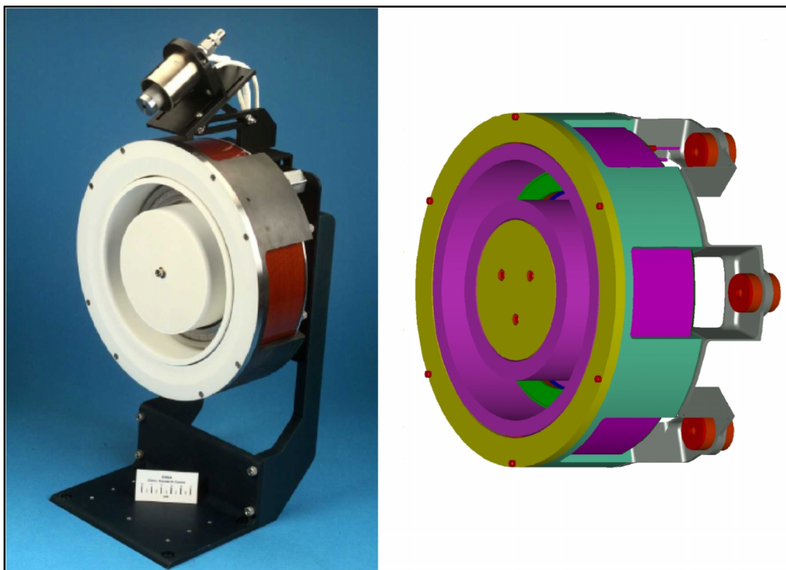

Figure 3. The NASA-173M V2 and HIVHAC Hall thrusters.

IV. Project Prometheus-Hall Thruster Research Task

A. Programmatic Background

NASA's Project Prometheus is developing nuclear power and propulsion technology that are enabling for NASA's mission to explore the universe and search for life. In addition to the proposed Jupiter Icy Moons Orbiter (JIMO) mission, which would be the first space science mission to utilize these technologies, Project Prometheus is sponsoring broad-based research and development efforts for future exploration applications. One such activity is the investigation of high-power, high specific impulse Hall thrusters.

During FY03, NASA GRC began investigating two approaches to achieve Hall thruster specific impulses greater than 4000 s at a 50 kW power level: 1) Utilizing lower molecular weight propellants and 2) Increasing the applied discharge voltage of xenon Hall thrusters. The feasibility of using krypton propellant to achieve the performance goals was demonstrated using the existing NASA-457M V1 Hall thruster. A discharge specific impulse of 4500 seconds was demonstrated at a discharge voltage of 1000 Volts and discharge efficiencies up to 64% were measured.[13] During FY04, a new high-power Hall thruster, designated the NASA-400M was designed to investigate high-specific impulse operation. A brief description of the thruster and the experiments conducted with the device are presented below.

B. FY04 Technical Accomplishments

The NASA-400M was developed to investigate high-power, high specific impulse Hall thruster operation. The design evolved from the NASA-457M V1, and incorporated improved electrical isolation, single piece inner and outer discharge rings (not segmented), an improved thermal design and refined hollow cathode. A photograph of the completed NASA-400M Hall thruster is shown in Figure 4. Following thruster assembly in November 2003, functional and performance testing was performed using both xenon and krypton propellant.

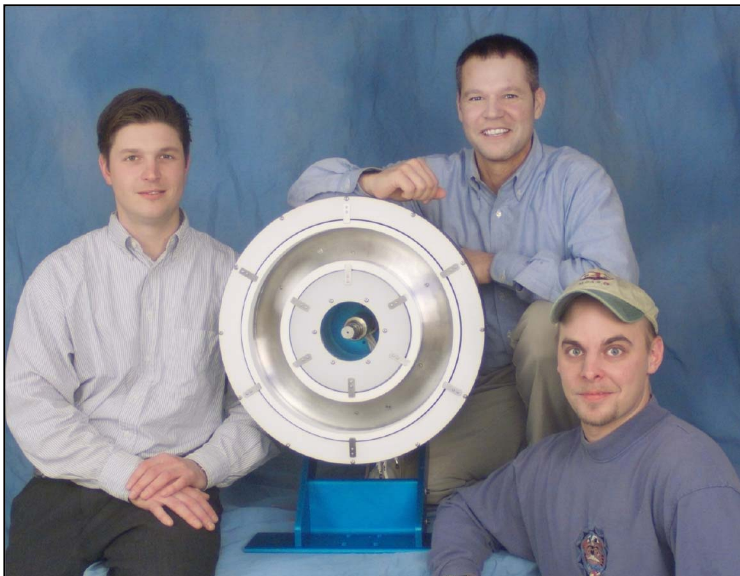

Figure 4. The NASA-400M Hall thruster shown with the members of NASA's Hall thruster team.

Functional testing of the NASA-400M was conducted at discharge powers from 3.6 to 47.0 kilowatts, by varying the xenon propellant flow rate between 20 and 75 mg/s and the discharge voltage between 200 to 600 Volts. The performance of the NASA-400M was improved compared to the NASA-457M for a given discharge voltage and comparable propellant density. For example, at a discharge voltage of 600 Volts the total specific impulse and efficiency of the NASA-400M was 2760 seconds and 0.60, respectively. Under similar conditions, the NASA-457M total specific impulse and efficiency were 2523 and 0.54, respectively. An anode isolator design deficiency, which prohibited operation above 600 Volts was identified during functional testing. The component was redesigned and integrated prior to initiating high voltage testing on krypton.

The performance testing of the NASA-400M operating on krypton propellant was investigated at discharge voltages up to 1100 Volts and stable operation was demonstrated up to 64 kW. A discharge specific impulse (calculated without cathode flow) of 4700 seconds was demonstrated at 1050 Volts, which is the highest specific impulse achieved with a NASA developed Hall thruster. This data point was collected at a discharge power of 43 kW and corresponded to a discharge efficiency (calculated without cathode flow and magnet power) of 0.65. The total specific impulse and efficiency is plotted as a function of discharge voltage for a constant mass flow rate of 26.0 mg/s in Figure 5. The total specific impulse range from 2250 to 3950 and total efficiency from 0.47 to 0.54. These data confirm that high voltage, krypton Hall thruster operation can be achieved at total thruster efficiency comparable to SOA xenon Hall thrusters.[14]

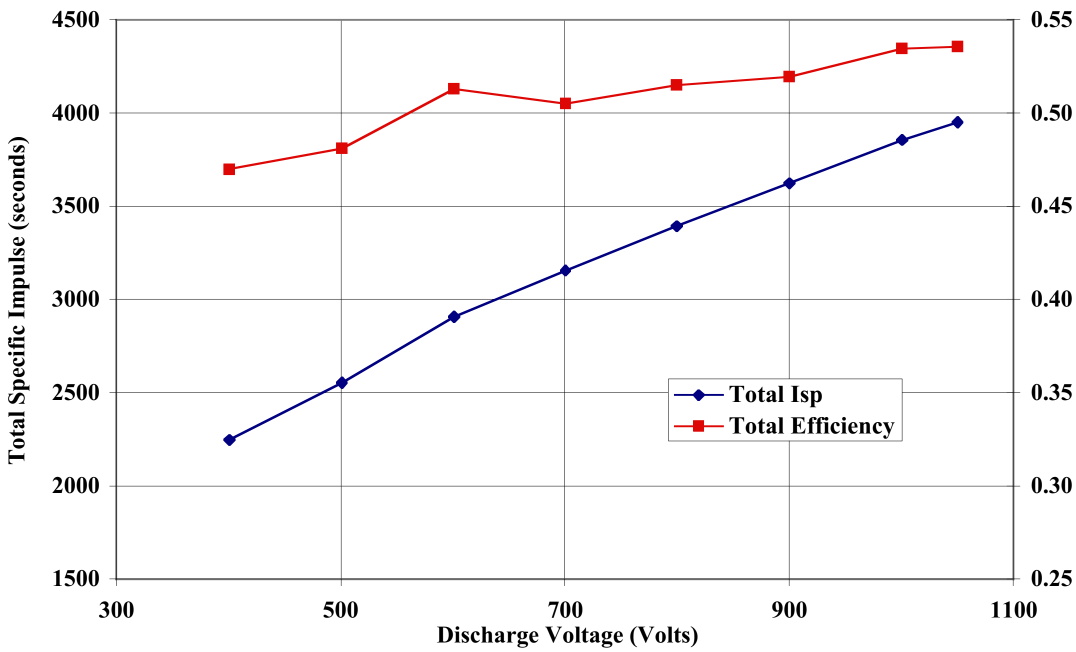

Figure 5. The NASA-400M total Isp and efficiency as a function of discharge voltage.

An extended duration firing of the NASA-400M will be performed to characterize high-power krypton Hall thruster erosion. The thruster will be operated at a discharge voltage of 700 Volts and discharge current of 40 Amperes for >200 hours. The erosion of the ceramic discharge channel will be measured using a previously described technique.[15,16] Several long duration (>10 hour) firings were conducted to facilitate selection of the operating point.

C. Out-Year Plan

Continued high-power Hall thruster activities will address critical technical challenges in the area of high-power Hall propulsion. During FY05 a 50 kW (500 Volt, 100 Ampere) breadboard discharge power supply will be designed and assembled. The supply will be based on a 10 kW DC-DC converter architecture module, developed by NASA GRC under the former MSM sponsored Energetics Project.[17] The 50 kW discharge supply will be integrated with the existing Prometheus Hall thruster and used to identify high-power Hall thruster power processing unit (PPU) integration issues. During FY05 experiments will be conducted to investigate thruster/PPU interactions, start transients and regulation of discharge current and discharge current sharing between modules.

V. Energetics Hall Thruster Program

A. Programmatic Background

The objective of the Energetics Project sponsored Hall thruster research is to discover and investigate mission enabling and enhancing Hall thruster concepts for NASA's primary and secondary propulsion applications. The project objective is achieved by solving the technical challenges, which enable the demonstration of critical Hall thruster function. Historically, the Energetics project has developed technology to a low-moderate level of maturity (TRL 3-4) and then transferred the technology to a user for development. Recently, NASA has been competitively selected to perform higher TRL technology development (TRL 4-6). For example, the moderate TRL, high-specific impulse Hall technology being developed under the HIVHAC program was initially developed under Energetics Project sponsorship. The FY04 Energetics Hall program includes the research activities in the following areas:

- Investigation of krypton Hall thruster plasma processes to enable the development of increasingly efficient krypton fueled Hall thrusters.
- Development of an analytic approach for predicting the lifetime of Hall thrusters.
- Development of a thermal modeling capability to improve the design of high power density, higher voltage (>300 Volt) Hall thrusters.

An overview of FY04 technical accomplishments in these areas is presented below.

B. FY04 Technical Accomplishments

1. Krypton Hall

The use of krypton as a propellant is attractive for NASA missions, which require both high-specific impulse and high-propellant throughput. Due to its low molecular weight, the theoretical specific impulse for krypton is 20% higher than xenon for a given voltage and the cost is 1/10 that of xenon. While past investigators observed reductions in krypton thruster efficiency up to 20% compared to xenon,[18,19] a previous performance evaluation of a high-power NASA thruster showed only slight a reduction in krypton efficiency compared to xenon.[13] These results indicated that additional insight into the krypton Hall thruster dynamics was necessary to design a high-efficiency krypton Hall thruster. FY04 efforts investigated krypton Hall thruster operation through a performance and plasma characterization of the 5 kW NASA-173M V2 Hall thruster, which has previously demonstrated both high-efficiency and high-specific impulse operation on xenon.[20,21] Analysis has shown that efficient operation of the NASA-173Mv2 on xenon was enabled through regulation of the electron current with the magnetic field.[21]

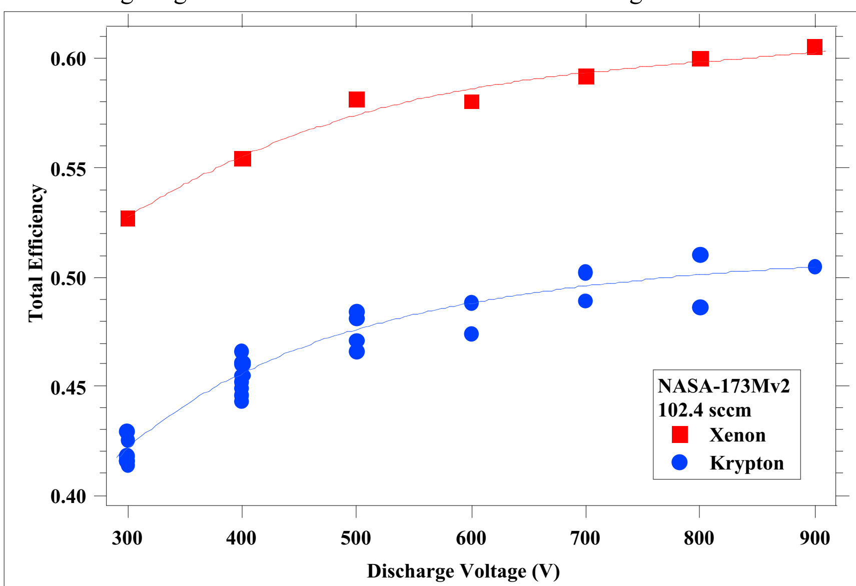

Figure 6. A comparison of the NASA-173M V2 efficiency operating on xenon and krypton.

Figure 6 shows recent results from a NASA-173M V2 krypton performance investigation compared to previously published data on xenon.[20] Operating on krypton propellant, the total efficiency was approximately 10% lower compared to xenon operation at the same volumetric flow rate. Plume diagnostics including a Faraday probe, RPA, and an ExB probe are being used to quantify the differences in xenon and krypton plasma parameters. Characterization of the NASA-173M V2 krypton plume will be performed in the fourth quarter of FY04. These experiments were conceived to identify krypton Hall thruster efficiency loss mechanisms and results are intended to guide further development of high-specific impulse, krypton Hall thrusters.

2. Analytic Lifetime Prediction

A simple analytic model was demonstrated that predicts Hall thruster channel erosion based on thruster geometry, operating conditions, and magnetic field configuration.[22] This model relies on a one-dimensional representation of the plasma with a fixed ionization fraction and variable ion energies based on the magnetic field distribution. Sputtering was modeled as the result of elastic scattering of ions by neutrals within the channel. Not all scattered ions and neutrals were assumed to reach the channel walls as a result of additional subsequent scattering events. Incorporating this phenomenon allowed the model to predict a decrease in erosion rate with time not predicted by only accounting for geometric effects. Figure 7 shows the favorable agreement between the predicted volumetric erosion rate and existing experimental data.[23]

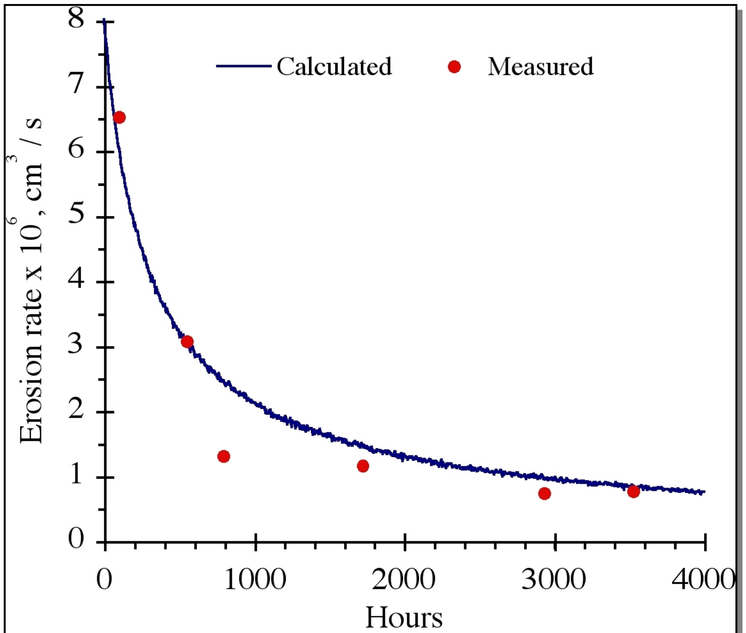

Figure 7. The analytic model erosion prediction compared to existing erosion data.

In the future this model will be used to predict the erosion of other Hall thrusters and/or operating conditions to determine if agreement with the existing erosion data was simply fortuitous or if such a simplified approach can be used for lifetime predictions. A sensitivity analysis to the input parameters will be performed and many of the simplifying assumptions will be re-evaluated. As currently configured, the code runs in less than two minutes suggesting that further increases in complexity would not necessarily be prohibitively computationally intensive. As a result we plan to investigate increasing the model to two-dimensions and using a plasma based model to predict neutral and plasma densities rather than relying on assumptions of propellant utilization fraction.

3. Thermal Characterization

Hall thruster operation has recently been investigated at discharge voltages and power levels significantly above SOA. Devices which operate at discharge voltages up to 500 Volts are being developed by U.S. industry[24,25] and operation has been characterized at discharge voltages over 1000 Volts.[26-28] NASA has developed thrusters which nominally operate at 50 kW, which have been tested at nearly 100 kW.[29] As the discharge voltage and thruster power level increase, improved thermal designs are required. Because an optimum propellant density is required for efficient operation, increases in the discharge voltage result in operation at power densities well above SOA Hall thrusters. The thermal design of the thruster must accommodate the increases in the power density to prevent overheating of critical components. The thermal expansion and thermally induced stresses in high-power Hall thrusters pose greater technical challenges compared to low-power devices, due to the physically large size of thruster components.

To address these technical challenges, thermal models of the NASA GRC designed Hall thrusters were generated. Three-dimensional, finite element thermal models were created for each thruster. The predicted temperatures were used to estimate thermal displacements and thermal stresses. Experimental thermal characterization tests were also conducted. The NASA-173M V2 Hall thruster and the NASA-457M Hall thruster were instrumented with thermocouples and operated until thermal state-state was reached. These tests were performed to validate the thermal model and refine the boundary conditions of the FEM's. The thrusters reached steady-state thermal equilibrium between 3.5 and 4.0 hours. Several extended duration firings (>4 hours) of the NASA-457M were performed. The results of the NASA-173M V2 and the NASA-457M thermal characterization tests are illustrated in Figure 8 and Figure 9, respectively.

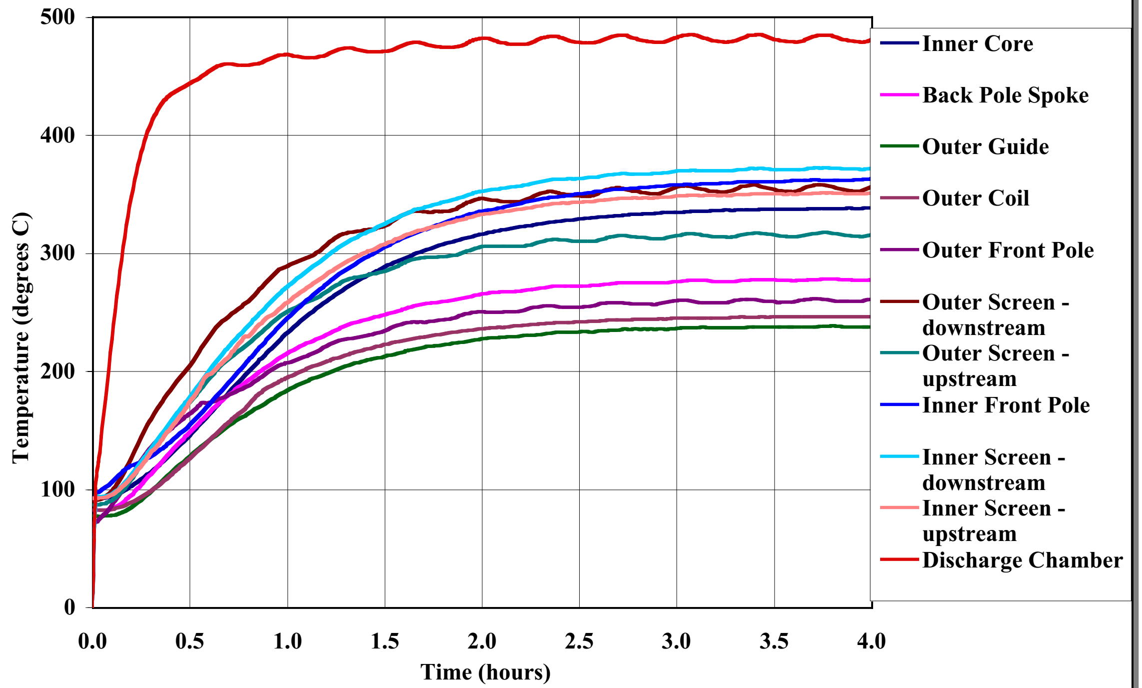

Figure 8. NASA-173M V2 thermal data at a power level of 5.5 kW (Vd=600 V, Id=9.26 A)

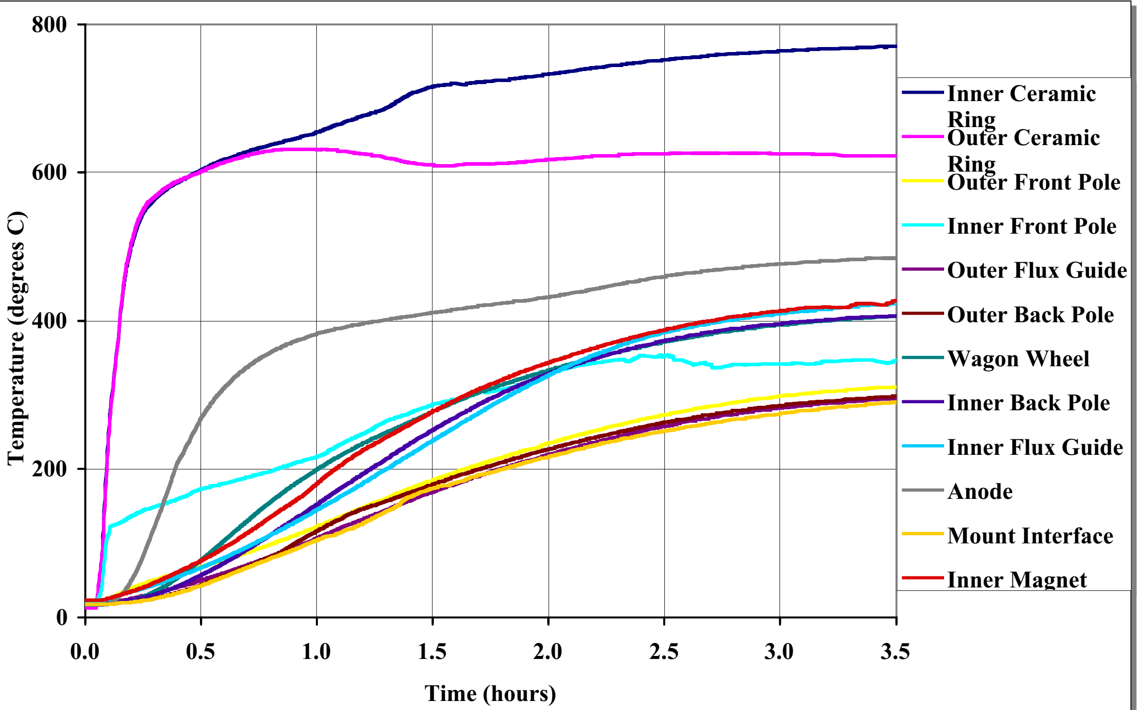

Figure 9. NASA-457M thermal data at a power level of 50 kW (Vd=500 V and Id=100 A).

C. Out-Year Plan
Electric propulsion research, including the low TRL Hall thruster development described above, has been performed under the sponsorship of the Energetics Project and the former Space Based Program. In FY05, the Energetics Project resources will be reallocated to support competitively selected, technology development projects, solicited under the Human and Robotic Technology (H&RT) Intramural Call for Proposals (ICP). Advanced electric propulsion was solicited under the H&RT's Advanced Space Technology Program, Power, Propulsion and Chemical Systems element. Only NASA Centers, including JPL were eligible to submit proposals in response to the ICP. A Broad Area Announcement will solicit externally led (non-NASA led) proposals in July 2004. The H&RT Programs will develop technologies in support of the National Vision for Space Exploration,[30] in accordance with NASA's Formulation Plan.[31]

VI. Summary

The Hall thruster development tasks conducted by NASA during FY04, under the sponsorship of the ISTP, Project Prometheus, and the Energetics Project, were described. Programmatic information, technical accomplishments and out year plans for each program element were provided. Under the sponsorship of the ISTP, the 50 kW NASA-457M V2 Hall thruster was developed to a TRL 4 and the 6-8 kW, 2200-2800 second HIVHAC thruster was designed. Under the sponsorship of Project Prometheus, a discharge specific impulse of 4700 seconds was demonstrated at 43 kW using the krypton fueled NASA-400M Hall thruster. An extended duration firing will be conducted to characterize thruster erosion. Under the sponsorship of the Energetics Project, the plume of a low power Hall thruster operating on krypton was studied, an analytic approach for predicting the lifetime of Hall thrusters was developed and a thermal modeling capability was developed.

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David T. Jacobson, David H. Manzella, Richard R. Hofer, and Peter Y. Peterson

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13. ABSTRACT ***(Maximum 200 words)***

An overview of NASA's Hall thruster research and development tasks conducted during fiscal year 2004 is presented. These tasks focus on: raising the technology readiness level of high power Hall thrusters, developing a moderate-power/moderate specific impulse Hall thruster, demonstrating high-power/high specific impulse Hall thruster operation, and addressing the fundamental technical challenges of emerging Hall thruster concepts. Programmatic background information, technical accomplishments and out year plans for each program element performed under the sponsorship of the In-Space Transportation Program, Project Prometheus, and the Energetics Project are provided.

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