Hydrogen Arcjet Technology Status

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Abstract

Over the past several years, the Ballistic Missile Defense Organization's Office of Innovative Science and Technology (BMDO/IST) has sponsored a multi-faceted research program aimed at the development of high power hydrogen arcjet systems for Earth-space missions such as orbit raising. BMDO's program funded a number of efforts in industry, university, and government laboratories to study critical issues such as performance, life, power processing, propellant storage and delivery, and spacecraft integration. While the BMDO hydrogen arcjet program has been terminated, it resulted in numerous advancements now being incorporated into on-going Air Force, industry, and NASA programs. This paper summarizes the progress made in the area of hydrogen arcjet systems under the BMDO program.

Introduction

Development of arcjet thrusters for Earth-space orbit transfer and trans lunar missions was initiated in the 1950's. At that time, high power, lightweight nuclear electric power (NEP) sources were anticipated (Ref. 1) and both NASA and Air Force sponsored programs focused on 30 kW-class hydrogen engines. A radiation-cooled, constricted-arc design was developed by the Avco Corporation and this device was successfully lifetested for one month at its design point specific impulse of 1000 seconds (Refs. 2,3). Efficiencies greater than 50 percent at 1000 seconds of specific impulse were reported with a regeneratively-cooled, subsonic arc thruster built by the Giannini Scientific Company (Refs. 4,5), and this thruster was also successfully lifetested. With the early 1960's came the realization that initial estimates of space-based NEP specific mass had been overly optimistic. This fact, coupled with the development of high performance chemical engines, led to the discontinuation of hydrogen arcjet development programs. A comprehensive review of arcjet efforts in the 1950 - 1960 time frame was published in 1965 (Ref. 6). It should be noted that most of the early efforts in this area focused on engine development and that very little attention was paid to power processing, integration issues, or propellant storage and management.

In the late-1980's, several circumstances resulted in the reconsideration of hydrogen arcjets for Earth-space orbit transfer. First, both advances in photovoltaic technology and the initiation of the SP-100 program promised availability of lightweight, high power sources for electric propulsion. Second, early Strategic Defense Initiative Organization (recently renamed the Ballistic Missile Defense Organization and hereafter referred to as BMDO) mission scenarios included platforms which required high power on orbit (for example, see Ref. 7). In these scenarios, power for electric propulsion would be available for orbit transfer if the required time to orbit could be tolerated. In this same vein, other Department of Defense mission planners were searching for ways to improve mission performance (Ref. 8). Finally, low power arcjet systems were nearing flight readiness (Ref. 9), reducing the perceived risks associated with this electric propulsion technology.

BMDO initiated a comprehensive high power, hydrogen arcjet system development program in 1988. Drawing from low power arcjet development experience, a number of efforts in industry, academe, and government institutions were funded to study critical issues such as performance, life, power processing, propellant storage and delivery, and spacecraft integration. A complete list of the program elements and participants is shown in Table 1. Over the past two years, the BMDO mission set has changed significantly and no longer includes platforms requiring high capacity power systems. Because of this, hydrogen arcjets are no longer viable candidates for BMDO applications and the program is being phased out in an orderly fashion. However, interest in hydrogen arcjet-based EOTVs in the aerospace community has not
Hwaned and the Air Force, NASA, and private industry are continuing to study arcjet systems for EOTV applications (see for example, Refs. 10-13). BMDO program support was directly responsible for many advances in hydrogen arcjet system development that will ultimately play a large part if hydrogen arcjet-based EOTV development goes forward. This paper provides a summary of the BMDO program accomplishments as it nears its completion.

Hydrogen Arcjet Technology Status

A BMDO-sponsored workshop was held in Galveston, TX to assess the state-of-art for 10 kW-class hydrogen arcjets for orbit transfer missions (Ref. 14). It was concluded that the technology base is adequate to support a focused electric orbit transfer vehicle (EOTV) development program. The workshop participants also concluded that a hydrogen arcjet-based EOTV could be designed, manufactured, and assembled in the 1997-1998 timeframe with acceptably low risk.

Propellant Storage and Delivery

Prior to the Galveston Workshop little thought had been given to hydrogen propellant storage and delivery systems for EOTV applications. In fact, at the time of the workshop, tankage fraction estimates ranged from less than 0.10 to approximately 1.0. Because of this uncertainty, a number of experts from the cryogenic community were invited to the workshop with the express purpose of developing a preliminary design and mass estimate for a propellant system to store hydrogen cryogenically and deliver it to the thrusters in the appropriate form. The group was also asked to assess the state-of-art and risks involved in the development of such systems.

Figure 1 shows a schematic of the system that resulted from the effort at the workshop. The group considered the functional requirements in addition to storage to be thermal control, pressure control, slosh control, propellant supply, and flowrate gaging. Each of these are discussed in detail in the workshop proceedings (Ref. 14). Briefly, the tank suggested was aluminum and was estimated to be approximately the same size as Centaur tanks now in use. The system eliminates long-term cryogenic storage requirements by utilizing the hydrogen as it is boiled off. An insulation system was included to limit the boil off rate both on the ground and in space and this system also incorporated a micrometeoroid/debris shield. A tank electrical heater was added to adjust the boil off rate as required over the mission and a thermodynamic vent system (TVS) was included for tank pressure control. Ring baffles in the tank were thought to be needed to control propellant motion. For propellant supply, the system includes a liquid acquisition device (LAD) to ensure both proper operation of the TVS and to allow for smooth starts of the propellant system in the low-g environment. A compressor, accumulator, and flow regulator, required to damp system transients and provide for steady flow to the thrusters, completed the propellant delivery system. Finally, gaging of both the hydrogen in the tank and the flowrate were deemed necessary for spacecraft control and to support mission operations.

The consensus of the workshop participants was that, for the most part, the system could be developed with existing technology. Exceptions included small development efforts for the compressor and possibly the flow regulator. The group also felt that the system could be flown operationally at low risk without prior flight verification but that this would require over-design in some subsystems to allow for operational uncertainties. Even with this stipulation, the tankage fraction was estimated to be on the order of 0.15.

Given the conclusion of the Galveston meeting, BMDO funded an effort at General Dynamics (GD) to investigate the feasibility of applying Centaur technology to an EOTV propellant storage and management system (Ref. 15). Figure 2 shows cutaway schematics of the resultant solar EOTV design and the EOTV packaged in a modified Centaur stage. The study showed that the hydrogen tank, the major structural element of the EOTV, could be fabricated using the same materials, methods, and tooling as are currently used in Centaur fabrication and the tankage fraction was estimated at 0.16. To minimize development requirements and risks, maximum use of Centaur components was assumed. For example, a separate study (Ref. 16) showed that the TVS developed previously for the Shuttle/Centaur could be used in this application with minor modification.

In GD's baseline case, an Atlas IIA was used to deliver the 30 kW EOTV and 2000 kg satellite to a 370 km circular orbit with an inclination of 28.5 degrees. The orbit transfer, with an assumed hydrogen arcjet specific impulse of 1200 seconds, required approximately 2450 kg of hydrogen and
200 days. The performance advantage to GEO over state-of-art solid or liquid chemical systems was found to be approximately 43 percent if the mass of the solar arrays was charged to the EOTV and in the range of 88 percent if the solar arrays were counted as useful payload. One major issue that surfaced concerned Atlas fairing requirements. The assumed payload was a ten foot fairing and for this it was estimated that a 10 to 13 foot fairing extension would be required. Previous GD study results for a different mission suggested that an eight foot extension could be accommodated and preliminary discussions did not rule out further lengthening. The final conclusions of the study, taken directly from GD's final presentation, are listed in Table II. In all, the study confirmed the conclusions of the Workshop and indicate that a hydrogen arcjet based EOTV development effort should not represent a technical high risk venture.

**Power Processing**

As with the propellant storage and delivery system, initial high power arcjet programs didn't include the development of flight-like power processing units (PPU). At that time, thruster testing was performed almost exclusively using ballasted laboratory supplies. In the more recent kW-class arcjet effort, parallel development of flight-like power processing hardware was viewed as critical to system deployment from the early stages of the program (Ref. 17). This same philosophy was adopted in the BMDO hydrogen arcjet program and a breadboard 10 kW-class PPU, shown in Figure 3, was designed, fabricated, and integrated with an arcjet thruster (Ref. 18). A full bridge topology was chosen with pulse width modulated current control similar to that used in the kW-class effort (Ref. 17). Isolation of the load from the input bus was chosen to mitigate integration issues. The unit also incorporated a pulsed starting circuit design developed for kW-class PPU's (Ref. 19). In laboratory tests, the breadboard unit demonstrated an efficiency of 0.94 and a specific mass of 2kg/kW was projected for a flight-packaged unit. While the unit derived control power from a 110 Vac input, a description of a power converter for operation from a 28 Vdc spacecraft bus was also described (Ref. 18).

As noted above, the breadboard PPU described was successfully integrated with a laboratory arcjet thruster. A similar unit was also recently loaned to the Phillips Laboratory for use in system integration tests for the Space Surveillance, Tracking and Repositioning (SSTAR) spacecraft power system test bed. In these tests, the PPU was integrated with a solar array simulator (functionally equivalent to the spacecraft bus being developed for SSTAR) and peak power control unit provided by TRW. This end-to-end testing was successfully completed at JPL and the PPU will now be used in further testing with a new arcjet electrode configuration.

In a separate effort sponsored by BMDO's SBIR program, an 30 kW, unisolated PPU based on a three phase buck regulator topology was developed (Ref. 20). A photograph of this device is shown in Figure 4. This technology was infused into a flight experiment when the basic design was chosen to operate the 26 kW ammonia arcjets on the Air Force-sponsored Electric Propulsion Space Experiment (ESEX). The flight unit in the ESEX program will also incorporate a pulsed starting circuit (Ref. 21) similar to the one developed for low power arcjets (Ref. 19).

**Advanced Diagnostics**

An advanced diagnostics program was instituted four years ago to provide data for 1) resolution of integration issues, 2) the identification and mitigation of performance and life limiters, and 3) model verification. This effort was performed primarily at Stanford University and significant progress was made toward the program goals.

Under the program, laser-induced fluorescence (LIF) techniques were developed and used to accurately measure flow velocity and kinetic temperature at exit plane of the nozzle of low power hydrogen arcjets (Refs. 22-26). The LIF technique developed provides the capability of measurement of three velocity components allowing the assessment of plume characteristics including swirl. Typical velocity profiles taken at varying axial positions in an arcjet plume are shown in Figure 5. A previous study of the plume of a high power ammonia arcjet indicated swirl velocities up to about 4 km/sec (Ref. 27). If real this represents a serious integration issue as swirl induced torques would have to be compensated by the vehicles reaction control system. At Stanford, little evidence of significant swirl velocity was found in the low power hydrogen arcjet. Measured exit plane temperatures were in the 4000 - 5000 K range implying that the arcjet core was fully dissociated. Another important finding was that facility effects were noticed on the arcjet centerline at backpressures of 1.5 Torr. This implies that that high quality vacuum chambers will be required to obtain flight-representative performance measurements. Finally, the LIF technique was used to measure slip velocities in
the arcjet plume. Doppler shifts of hydrogen and helium in the plume of an arcjet running on a mixture of these two gases were measured. The data indicate that, while there are significant differences in the masses of these species, the velocities are identical within the measurement uncertainty. This implies that the velocity of the hydrogen atom at the exit plane of the thruster accurately reflects the mean bulk velocity of the flow. The LIF technique has now been fully verified and is ready for application at other experimental sites.

The data generated through BMDO program efforts has also been used in the first comparisons of hydrogen arcjet properties to the results of CFD models generated in other programs (Refs. 28,29). These studies show that while single fluid computational models do capture qualitative features of the performance characteristics of the device, specific impulse is overpredicted by approximately 20 percent. This, in turn, has led to further modeling efforts. In all, the database generated to date will serve as an excellent benchmark for code validation.

In addition to the LIF experiments, emission spectroscopy has recently been used to measure electron number densities close to the cathode and to estimate cathode temperatures in an in-situ, nonintrusive fashion (Ref. 30). Initial results indicate number densities much higher than those predicted by state-of-art codes. However, the measured cathode temperatures are consistent with the often used assumption that the cathode is molten with a temperature very near the melting point of tungsten.

In other efforts aimed at better understanding speciation in the flow, a laser-based Raman scattering technique was developed to quantify molecular hydrogen populations (Ref. 31) and a vacuum ultraviolet absorption technique for the measurement of ground state atomic hydrogen number densities was also explored (Ref. 32).

The diagnostics developed under the BMDO program now provide a means to understand the characteristics of the hydrogen arcjet flowfield. The data generated to date also provide an excellent benchmark for the validation of computational models now under development. In addition, the diagnostic development has had significant carry over into the BMDO’s present xenon thruster evaluation program as the experimental techniques are, in general, directly applicable to the characterization of xenon plasma flows (for example, see Ref. 33).

Performance and Life

While the extended tests at Avco and Giannini in the early 1960’s showed reasonable cathode wear, recent tests at higher performance levels on ammonia (Ref. 34) and with hydrogen (Ref. 35) have shown that cathode life is a major issue as shown in Figure 6. In particular, the formation of whiskers around the attachment crater can be a life limiting phenomena. A BMDO-sponsored Workshop was held in 1989 specifically to address the cathode erosion issue (Ref. 36). Following this workshop, the BMDO program initiated a concentrated effort to explain and mitigate phenomena responsible for cathode degradation in high power arcjets.

Most of the research on cathode degradation concentrated on 1) the development and evaluation of degradation resistant electrode materials and 2) the study of effects of power conditioning, propellant, and electrode geometry on cathode lifetime. Texas Tech University (TTU) was responsible for most of the research (Refs. 37-42) and automated vacuum facilities (see Figure 7) and a modular arcjet simulator were developed at TTU. For safety, most of the tests were run using nitrogen as the propellant gas at the beginning of the program and these tests provided many general conclusions. Specific experiments designed to provide correlations between the nitrogen results and hydrogen are being completed as the program is concluded. A series of materials, chosen for their high temperature strength and emission characteristics, were tested under controlled conditions to compare mass loss rate and tip conditions (Refs. 38,39). The results of this screening are shown in Figure 8 and clearly indicate that thoriated tungsten based materials were superior to the others tested. In further tests, increasing the thorium oxide concentration (to 4% as opposed to the typical 1-2%) was found to reduce steady state erosion. In these tests, it was also found that steady state erosion increased with time and that the cathodes with lower thorium oxide content exhibited more whisker growth. This is consistent with the hypothesis that erosion degradation increases as the thorium oxide is depleted from the tip. However, the increased mass loss with time is not consistent with prior tests of low power arcjets. This may be due to differences in experimental conditions and further examination of this phenomenon is needed. Other tests which showed erosion rates to be dependent on the cross-sectional area of the cathode and on current level were consistent with earlier findings as was the finding that erosion on
ignition is significantly higher than at steady state. These results suggest that arcjet lifetime can be increased by 1) using large diameter cathodes, 2) designing the thruster to maximize discharge voltage at a given input power level, and 3) devising methods to limit starting transients.

Recent interactions have shown that Russian materials science is very advanced, particularly in the area of high temperature refractories. Through Texas Tech University, large samples of single crystal (SC) tungsten and SC tungsten containing three percent niobium were recently obtained. Both of these materials will be tested as potential high temperature anode materials for high performance arcjets in the very near future.

In a separate set of tests, current ripple was found to have a profound effect on erosion (Ref. 40). In those tests, thoriated tungsten cathodes were operated at 250 A with current ripple values between about 1 and 25 percent. Results indicated that steady state erosion rates decreased with increasing ripple magnitude up to approximately 15 percent. Beyond 15 percent, the discharge was found to be unstable and the erosion rates rapidly increased. A qualitative model (Ref. 41) was developed which is consistent with the observed results (see Figure 9).

At LeRC, early hydrogen arcjet program efforts focused on performance assessments of a number of designs. For this, a thrust stand was fabricated and installed in a test port attached to a large vacuum facility (Figure 10). At the same time, lifetesting facilities (see, for example, Figure 11) were also developed to allow endurance tests of the most promising designs. Hydrogen delivery capacity was sized to allow 500 to 1000 hours of continuous testing.

At the beginning of the program, it was anticipated that specific impulse levels above the 1000 second design point chosen in the 1960's programs (Refs. 2-5) would be required for optimized orbit transfer applications. One of the conclusions of the Giannini efforts was that regeneratively-cooled, subsonic arc devices were limited by thermal constraints to performance levels near 1000 seconds. Also, it was thought that the maximum power available for orbit transfer would be about 30 kW, and that multiple thrusters would required. It was therefore felt that the operating range of a flight-type thruster would be in the 10 to 15 kW range. The radiation-cooled, constricted-arc device was chosen for initial testing. Parametric testing of an arcjet was carried out to evaluate a number of nozzle designs at power levels between 5 and 42 kW (Ref. 43). With one of the nozzles used in this series of tests, a specific impulse value of 1460 seconds was attained at approximately 30 percent efficiency. The highest efficiency measured was 34.4 percent at a specific impulse of about 1050 seconds. To explore performance limits, the nozzles were tested to destruction. Post-test examination revealed that cathode erosion was small and limited to the cathode tip. Extended tests, however, indicated that significant whisker growth occurred at high specific impulse levels. This issue will have to be addressed if the development of arcjets of the radiation-cooled, constricted-arc design is pursued. Tests to examine the impacts of various parameters on cathode life are in progress in an on-going program (Ref. 35).

Continued inputs from potential users indicated that trip time reductions were attractive and that specific impulse could be reduced to levels nearer 1000 seconds if efficiency could be increased. In response, a reevaluation of both radiatively- and regeneratively-cooled, subsonic-arc, 30 kW thrusters first developed by Giannini in the 1960's was undertaken (Refs. 44). Thrusters replicating (to the extent possible given the design details available) the Giannini designs in critical areas were fabricated and tested. A photograph of the regeneratively-cooled device is shown in Figure 12. The goal was to reproduce the performance attained in the early program and to gain insight on the scaling relationships required for optimal performance at the 10 - 15 kW level. When operated at the design point, the performance of the radiation-cooled version was slightly below that reported previously (Ref. 4). The nozzle area ratio on the 1960's device, however, was nearly twice as large as was the one used in the tests reported in Ref. 44 and subsequent cold flow measurements with a nozzle extention indicate that this design feature could account for much of the difference. Testing of the thruster with an extended nozzle is continuing.

Of most interest were the results obtained using the regeneratively-cooled design. As noted previously, this device had demonstrated specific impulse of 1000 s at approximately 0.50 efficiency at its design point in the 1960's development program. In recent tests at LeRC, thruster performance at the 1960's design point was about 950 seconds specific impulse at an efficiency of 0.39. The discrepancy in performance between the two periods is as yet unexplained. It is possible that design subtleties were overlooked in the recent effort because detailed drawings of the 1960's hardware were unavailable. Some design
improvements, such as the addition of radiation shielding to mitigate thermal losses, are thought to be possible. These have now been implemented and testing under the continuing NASA program is anticipated in the near future.

In addition to the thruster development work at LeRC, an effort to scale and optimize the Giannini-style thruster was performed by the Rocket Research Co. (Ref. 45). To start this effort, a thorough literature search was performed. Scaling relationships were then developed to determine critical dimensions. Both plasma analyses and finite element thermal codes were used in the design effort and a 10 kW design was fabricated (Figure 13) and tested. The thruster operated stably from 4 to 10 kW and showed very little wear over 20 hours of testing. Efficiency levels attained with this device were significantly above those typically attained with conventional constricted arc designs below 950 seconds of specific impulse. Above this specific impulse level, however, the efficiency was lower than that achieved with conventional devices. Further testing of this device will take place at LeRC in the near future under the continuing NASA-sponsored program. Three additional nozzles, designed to provide parametric variation of critical dimensions, have been fabricated for this testing.

From the above it can be seen that further efforts will be required to bring arcjet technology to an acceptable level for application with respect to both performance and lifetime and the BMDO-sponsored program efforts provide an excellent starting point for future research programs. A thorough materials screening has been performed and system parameters affecting cathode erosion have been identified. Also, a large data base detailing the impacts of geometry is now available. Several design features which should lead to improved performance have been suggested and these will shortly be implemented and tested under an ongoing program.

Modeling

In addition to system and component level studies, the BMDO program also sponsored a modeling effort at the University of Tennessee Space Institute (Refs. 46-51). The Navier-Stokes solver used is based on a modified SIMPLE algorithm (Refs. 52,53). This code had previously been modified at UTSI to describe both laser induced plasmas (Ref. 54) and radio frequency argon plasmas (Ref. 55). In the model, flow is assumed to be laminar, viscous, axi-symmetric, and time steady. The wall and inlet temperatures are specified along with the mass flow, total current and total power. Based on earlier experiments with low power hydrazine arcjets (Ref. 56), a linear distribution of current across the anode was assumed.

In the course of the effort, the accuracy of the transport properties used in the calculations were found to be critical to attaining realistic results. Early assumptions of chemical and thermodynamic equilibrium were relaxed as initial runs using these assumptions did not appear to adequately describe the spatial distribution of transport properties and could not account for recombination in the nozzle. To treat chemical non-equilibrium, three species equations were required and an energy equation for the electron gas was added to treat thermodynamic non-equilibrium. The code has been tested against experimental data from a 30 kW hydrogen arcjet (Ref. 47). Predicted specific impulse and efficiency were about 15 and 30 percent lower, respectively, than the experimental values. The difference between experimental and calculated performance values is mainly attributed to uncertainties in boundary conditions and in transport properties and reaction rates used in the model.

The initial goal of the modeling effort was to develop a predictive code to determine the ultimate performance limits of the arcjet thruster. The effort to date has illustrated that the difficulty of this task is due to the extremely complex nature of the arcjet flow field. While the ultimate goal was not attained, the available code is useful in examining trends and the lessons of the effort will serve as a basis for future modeling efforts.

Very High Power Devices

In anticipation of very high power sources from the SP-100 project, the BMDO program also sponsored an effort to expand the envelope of operation to power levels above 30 kW. The work was performed at the Institute for Spaceflight Systems (IRS) of the University of Stuttgart (Ref. 57). The IRS's laboratories (see Figure 14) are equipped with large vacuum chambers with very high mechanical pumping speeds and have very high power capabilities.

A water-cooled laboratory model high power arcjet (HIPARC) was fabricated for this effort at the IRS. Designed for the 100 kW power level, this thruster incorporated a segmented nozzle so that both energy and anode current distribution could be measured across a wide range of operating
conditions. The cathode tip was also easily removable so that a number of different cathode configurations could be evaluated. A schematic of the device is shown in Figure 15. Testing was performed on a thrust balance to provide performance measurements.

The HIPARC was run with several different cathodes at power levels between 10 and 120 kW at specific power levels between 10 and approximately 500 MJ/kg (Ref. 57). Typical performance data are shown in Figure 16. Specific impulse values near 1500 seconds were obtained at the highest specific powers tested. At specific impulse levels above 1000 seconds, efficiencies were typically below 25 percent. Mass flow rate was found to have a major influence on performance with an optimum near 200 mg/s. Current distribution was measured as was the energy deposition at the walls to provide insight into heat loading for further design work. Three cathode tips were evaluated and test results suggest that larger diameter cathodes are preferred. These tests also indicated that premachining an arc crater into the tip increased stability and reduced the burn-in time.

Together, the results of this program are very encouraging. Clearly, high specific impulse (Isp > 1000s) can be obtained with high power devices and the efficiency is expected to improve using a more flight-like radiation- or regeneratively-cooled device. In anticipation of this, a radiation-cooled thruster design was completed at IRS and this device could be fabricated and tested at a later date.

**Concluding Remarks**

The BMDO program was responsible for a number of advances in the state of the art of hydrogen arcjets. A design for a practical propellant storage and delivery system was generated and implementation was found to be feasible mainly using existing technology. Development of the power processor was addressed and both isolated and non-isolated units were fabricated. These topologies have both been baselined for use in Air Force-sponsored flight demonstrations. The arcjet starting technique developed under the program has also been baselined for use in the Air Force programs. Advanced optical diagnostic techniques have been developed and applied to provide information critical to propulsion system integration. These techniques are not specific to the arcjet and are now being applied to plume characterization in the current BMDO xenon thruster evaluation program. Performance and endurance testing under the program uncovered issues that will need to be resolved before the arcjet can be considered for practical application. A modeling effort provided a code useful in examining trends in arcjet performance with respect to geometry and operating conditions. Finally, significant progress was made toward the development of high performance, long-lived thrusters. While the BMDO hydrogen arcjet program has been terminated, it has resulted in numerous advancements incorporated into ongoing Air Force, industry, and NASA programs.

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**References**


Table 1. BMDO/IST Hydrogen Arcjet Technology Development Program Elements.

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Table 2. General Dynamics EOTV Design Study Conclusions.

- A high performance solar-powered EOTV can be achieved using existing Centaur Tank Technology and manufacturing methods.
- The EOTV concept allows 43% to 88% increase in useful payload to GEO, depending on whether the satellite uses the EOTV solar panels.
- The propellant tank can be insulated with flight-proven Centaur fixed foam insulation and multi-layer insulation.
- Propellant motion in the tank is very well-behaved, and control baffles probably aren't needed.
- Tank pressure control can be accomplished with a modified Shuttle/Centaur zero-g thermodynamic vent system.
- The propellant supply is simple and draws from available technology; the most significant development is a low-capacity gas compressor.
- The EOTV and its payload have been configured for launch by a structurally-enhanced Atlas IIA with an enlarged payload fairing.
- Recommended follow-on studies include EOTV preliminary design and further analysis and design to support launch vehicle integration.
Figure 1. Hydrogen Arcjet Propellant System Schematic (Ref. 14).
a) Cutaway Schematic of the Centaur-based EOTV.

b) Schematic of EOTV in a Modified Centaur Stage.

Figure 2. EOTV Design Schematics from the General Dynamics Feasibility Assessment (Ref. 15).
Figure 3. Photograph of the 10 kW-Class Breadboard Power Processing Unit (Ref. 18).

Figure 4. Photograph of the 30 kW-Class Power Processing Unit (Ref. 20).
Figure 5. Arcjet Exit Plane Velocity Profiles Obtained Via LIF Technique at Stanford University (Ref. 24).

Figure 6. Tungsten Whiskers on the Cathode of a High Power Arcjet (Ref. 35).
Figure 7. Cathode Erosion Test Facility at Texas Tech University.

Figure 8. Long-Duration Cathode Erosion Rates for Various Candidate Materials (Refs 38,39). (Cathodes tested for 100 hrs at 250 A (13% ripple); mass flow rate = 4x10^-4 kg/sec N2).
Figure 9. Effects of Power Conditioning on Cathode Erosion (Ref. 41).

Figure 10. Hydrogen Arcjet Performance Test Stand at LeRC.
Figure 11. Arcjet Lifetest Facility at LeRC.

Figure 12. Regeneratively-Cooled 30 kW-Class Hydrogen Arcjet Tested at LeRC (Ref. 44).
Figure 13. Scaled Regeneratively-Cooled Arcjet Tested by the Rocket Research Company (Ref. 45).

Figure 14. Test Facilities at the Institute for Spaceflight Systems, University of Stuttgart.
Figure 15. A Schematic of the HIPARC 100 kW-Class Thruster Tested at IRS (Ref. 57).

Figure 16. Typical HIPARC Performance Data (Ref. 57).