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Electric Propulsion Applications and Impacts

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ELECTRIC PROPULSION APPLICATIONS AND IMPACTS

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Most space missions require on-board propulsion systems and these systems are often dominant spacecraft mass drivers. Presently, on-board systems account for more than half the injected mass for commercial communications systems and even greater mass fractions for ambitious planetary missions. Anticipated trends toward the use of both smaller spacecraft and launch vehicles will likely increase pressure on the performance of on-board propulsion systems. The acceptance of arcjet thrusters for operational use on commercial communications satellites ushered in a new era in on-board propulsion and exponential growth of electric propulsion across a broad spectrum of missions is anticipated.

NASA recognizes the benefits of advanced propulsion and NASA's Office of Space Access and Technology supports an aggressive On-Board Propulsion program, including a strong electric propulsion element, to assure the availability of high performance propulsion systems to meet the goals of the ambitious missions envisioned in the next two decades. The program scope ranges from fundamental research for future generation systems through specific insertion efforts aimed at near term technology transfer. The On-Board propulsion program is committed to carrying technologies to levels required for customer acceptance and emphasizes direct interactions with the user community and the development of commercial sources. This paper provides a discussion of anticipated missions, propulsion functions, and electric propulsion impacts followed by an overview of the electric propulsion element of the NASA On-Board Propulsion program.

INTRODUCTION

The aerospace industry has changed significantly over the past several years and continued change is anticipated into the near future. At present, tremendous pressure is being exerted to assure cost-effective mission performance both in commercial and government sectors. This pressure will force the development and application of revolutionary new technologies across a broad range of mission sets. Several important emerging technology drivers are shown in Table 1. On-board propulsion systems are required in nearly every mission scenario and these systems are often dominant spacecraft mass drivers. This is true both for traditional spacecraft such as large geosynchronous communications satellites, and for the spacecraft being designed for distributed low- and mid-Earth orbital communications systems, commercial remote sensing, and ambitious Earth and space science missions. Examples of typical spacecraft mass fractions for several mission classes are shown in Figure 1 and these data clearly indicate that on-board propulsion is an area of high leverage for improved mission performance.

Electric thrusters can provide significant fuel economies as compared to their chemical counterparts (from factors to an order of magnitude depending on the system and application) and acceptance of these systems is beginning to occur. The potential benefits of electric propulsion were well displayed in the recent use of 1.8 kW arcjet thruster systems (Ref. 1) for north-south stationkeeping (NSSK) of the first Lockheed Martin Astro Space (LMAS) Series 7000 geosynchronous (GEO) communications satellite. The mission average specific impulse provided by the arcjet was more than 1.5 times that offered by state-of-practice (SOP) resistojet and bipropellant chemical systems and, in the first mission, propellant savings were used to significantly reduce launch vehicle requirements. First generation arcjets are now scheduled to fly on at least ten more LMAS Series 7000 spacecraft and advanced arcjets, shown in Figure 2, were recently accepted for a next generation GEO satellite series (Ref. 2). In fact, every major GEO communications spacecraft manufacturer now offers an electric propulsion option for NSSK (see, for example, Refs. 3, 4). Electric systems will be used to perform other mission functions in the near term. For example, resistojets will be used for the insertion of a near-term distributed communications system and higher performance options are being considered for insertion/maintenance, and deorbit of future low- and mid-Earth orbit (LEO/MEO) spacecraft. Ion propulsion being developed under NASA's Solar Electric Propulsion Technology Application and Readiness (NSTAR) program was recently

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baselined for use on the first New Millenium spacecraft - the first use of an electric thruster for primary propulsion in an ambitious (high delta-V) planetary mission. In fact, a general trend toward the use of electric propulsion, shown in Table 2, is anticipated and these applications will be discussed in some detail in the body of this paper.

NASA's Office of Space Access and Technology (OSAT) recognizes the benefits of advanced propulsion and supports an aggressive On-Board Propulsion program, including both electric and low thrust chemical propulsion elements, designed to assure the availability of high performance on-board propulsion systems for both near and far term missions. The scope of this program ranges from fundamental research through specific technology developments, to efforts aimed at technology transfer. OSAT also recognizes the synergism between advanced electric propulsion and power systems and has developed an integrated On-Board Power and Propulsion Strategy (Refs. 5, 6) to ensure the simultaneous advancement of these two critical technologies. This strategy assumes that the needs for higher performance propulsion and power systems will increase over the next decade. OSAT, working in cooperation with industry and other government progams, is committed to carrying critical technologies to levels required for customer acceptance. Direct interactions with the user community and the development of commercial sources for program-sponsored technologies are strongly emphasized. This paper provides a discussion of both anticipated missions and propulsion functions followed by an overview of the electric propulsion element of the OSAT On-Board Propulsion (OBP) program. Details of the overall program can be found in a recent review (Ref. 7).

CLASSES, MISSIONS, REQUIREMENTS, & PAYOFFS

Electric propulsion devices fall into three general catagories denoted by acceleration mechanism - electrothermal, elecrtostatic, and electromagnetic. Examples and a brief description are shown in Figure 3. Each class has attributes attractive for certain mission applications. For example, electrothermal thrusters offer the highest thrust-to-power ratio and operate on hydrazine, making them compatible with many existing spacecraft propellant systems. Electrostatic systems offer very high specific impulse levels and so are excellent candidates for missions with very high delta-V requirements. Electromagnetic systems, can be operated in low power pulsed modes making them attractive for missions requiring small impulse bits or where modest total impulse is required and power and simplicity are at a premium. Figures 4a and 4b illustrate required propulsion functions for Earth-orbit and planetary spacecraft. To cover the disparate mission requirements. This section provides descriptions of several mission classes and required propulsion functions along with a description of potential roles for electric propulsion.

GEO SPACECRAFT

Commercial GEO comsats will continue to be a major space sector and fierce competition in this arena is expected to drive technology development and application for the forseeable future. Current trends are toward increased power levels and it is expected that advanced electric propulsion systems will be used to perform primary propulsion functions in addition to the traditional NSSK role. Advancement in this direction will probably be evolutionary, with electric propulsion used first to improve mission performance through apogee topping. A recent study indicates that the use of electric propulsion systems for the final segment of the tranfer to the GEO orbit can increase net spacecraft mass by 20 to 45 percent depending on available power and allowable trip times (Ref. 8). Figure 5 shows the general mission orbital strategy for this hybrid type of mission. Higher performance electric power and propulsion systems (high specific impulse, greatly reduced specific mass) will allow the consideration of full electric orbit transfers. In addition to the commercial community, the Department of Defense (DOD) also has a strong interest in the use of electric propulsion for GEO missions (see, for example, Ref. 9). In addition to NSSK and orbit transfer functions, DOD mission requirements may also include on-orbit repositioning. Compared to SOP chemical systems, high performance electric thruster systems can be used to reduce the propellant load required per reposition manuever for a fixed transfer time or to reduce the time required for reposition. Figure 6 (Ref. 10) shows the potential benefits of advanced electric propulsion for a GEO mission in which the on-board system is used to provide both NSSK and two repositions per year. For this study, a SOP hydrazine system was compared to arcjet, ion, and Hall thruster systems for various launcher specific GEO spacecraft masses and lifetimes. The data (shown for the Atlas 2AS launcher case) clearly indicate the value of electric propulsion for typical mission lifetimes (i.e. > 7 years). In the case of a fixed launch vehicle, the savings provided by electric propulsion can be used to extend satellite

life (currently a high priority DOD goal) or to increase payload.

LEO/MEO SPACECRAFT

Over the past several years, significant attention has focussed on the LEO/MEO space sector. Distributed LEO/MEO communications systems are being developed by several major commercial concerns and growth in this area is anticipated into the forseeable future. Growth in small satellite Earth-science and commercial remote sensing missions is also anticipated. Mission propulsion functions will include orbital insertion, orbit control, and deorbit. Distributed system concepts will entail both new requirements and constraints. Effective launch strategies, for example, will maximize the number of spacecraft per launch vehicle and this, in turn, sets specific constraints on spacecraft weight and volume. Assembly line production philosophies will stress the development of simple, low cost, benign propulsion systems. Also, deorbit requirements will be levied on this mission class. These considerations emphasize the importance of on-board propulsion and provide a unique opportunity for the use of advanced electric propulsion. Both arcjet and Hall technologies are well suited for applications such as insertion, maintenance, and deorbit of MEO satellites. This is particularly true for the comsat case as these spacecraft have significant power available for propulsion functions. In one recent proprietary study, the use of electric propulsion for orbital insertion was found to reduce propulsion system mass by a factor of two and volume by a factor of three over the proposed chemical baseline without changing the spacecraft power system. For this mission, the time penalty associated with electric propulsion was between two and three months. Recent mission analyses (Refs. 11, 12) show that electric propulsion can greatly benefit even very power limited Earth-orbital missions. One mission chosen for study was the Total Ozone Mapping Spectrometer (TOMS). In this analysis, a low power pulsed electric propulsion system was compared to the hydrazine thruster system actually used. Results of this analysis are shown in Figure 7 and indicate that the TOMS payload could be increased by more than 50 percent in the TOMS mission as designed and more than 120 percent if a deorbit requirement were levied as would be the case if the mission were designed in todays environment. In addition, the solid propellant-based pulsed system (described below) eliminates safety and environmental costs/hazards related to the use of hydrazine thrusters.

SPACE SCIENCE

Fast, cost-effective, high return missions are the clear goal of NASA's planetary exploration program. Propulsion is a primary spacecraft mass driver in virtually all planetary-class missions. In fact, propulsion mass fractions are on the order of 50 percent in modest delta-V missions like the one shown in Figure 1 and can range to more than 70 percent for ambitious, high delta-V missions. Figure 4b shows that typical planetary missions entail both primary and auxiliary propulsion. To date, propulsion functions in NASA-sponsored space science missions have been performed exclusively by chemical systems. Primary electric propulsion systems can greatly enhance this mission class by reducing launch mass requirements, alleviating time window constraints, and both reducing trip times to and extending stay times at selected celestial targets. Kakuda, Sercel, and Lee (Ref. 13) recently showed that high performance ion propulsion systems could deliver substantial payloads to small bodies such as the asteroids Vesta or Ceres or the comet Kopff in a cost effective fashion. While the efficacy of ion propulsion technology for high delta-V missions has long been known, it is interesting that even moderate specific impulse systems like the hydrazine arcjet can provide significant benefits in certain planetary-class missions. This was shown in a recent proposal to NASA's Discovery program in which arcjets were considered as an alternative to a conventional hydrazine monopropellant system for a sample and return mission to the asteroid Nereus (NEARS). NEARS mission analyses showed that replacing the SOP monopropellant system with a 400 second specific impulse arcjet could both double the stay time (from 70 to 140 days) and more than double the mission mass margin (from 10 to 24 percent) without changing the spacecraft power system.

Other space science missions can be enhanced/enabled by electric propulsion. For example, precision orbital control/positioning will be required for the interferometric missions and this could be provided effectively by pulsed plasma thrusters designed to provide verly small impulse bits. Pulsed systems may also be used to eliminate SOP chemical systems for attitude control on planetary missions. Further, spacecraft arrays requiring orbital insertion can benefit from low power systems similar to those used in MEO constellation deployments.

NASA ELECTRIC PROPULSION PROGRAM DESCRIPTION

Innovative new propulsion technologies will be required to meet the stringent performance goals anticipated in evolving mission scenarios such as those discussed in the preceeding section. NASA's OSAT supports an aggressive On-Board Propulsion (OBP) program to identify, develop, and transfer high performance propulsion technologies for both near- (3 - 5 year) and far- (5 - 10 year) term missions. Both electric and chemical elements are included (Ref. 7) to cover the broad range of mission requirements and the electric propulsion element includes efforts in each of the three major electric thruster classes. Many of these technologies cross cut several missions and every effort is made to assure that the sponsored technologies are capable of performing multiple missions. To ensure that concepts are carried from conception to insertion, the program is scoped broadly and includes fundamental research, technology development, and directed technology insertion efforts. The program maintains flexibility to respond to technology transfer opportunities as they arise and works cooperatively with all sectors of the areospace community. As noted above, the electric propulsion element is complemented by a stong power technology program (Ref. 5). OSAT also supports a focused NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program, led by the Jet Propulsion Laboratory (JPL) in partnership with LeRC, to develop and demonstrate a 0.5 - 2.5 kW, 55% efficient ion system (Isp ~ 3100 sec) that will enable launch vehicle class reductions as well as significant trip time savings for small satellite planetary missions . NSTAR was initiated in FY93 and has baselined 30-cm ion engine technology developed under the OBP program. The NSTAR system has now been chosen for the first mission in NASA's New Millennium program.

The following section provides a description of the electric propulsion element of the OBP program with an emphasis on recent progress and program directions. Near term thrust areas are shown in Figure 8 for reference.

Electrothermal Systems

As noted above, first generation arcjets are now in operational in the commercial market. These arcjet systems were developed through joint OBP/industry efforts which included fundamental feasibility demonstrations, contracted development and validation efforts, and cooperative arcjet/spacecraft integration assessments. The arcjet program was recently reviewed in detail (Ref. 14). Following the transfer of first generation arcjets, a 600 second, 2 kW-class arcjet system development program was undertaken in response to a known user need (GEO NSSK) and to provide technology for anticipated LEO/MEO satellite insertion and deorbit requirements. The OBP program-sponsored part of advanced arcjet development effort recently completed a successful qualification-level demonstration of a flight-type system. With the recent acceptance of this technology, the OBP program has now focused attention on the development of low power arcjets (LPATs) for power-limited spacecraft. Over the past year, sub-kW arcjet systems have been considered for application to LEO/MEO orbit insertion, NSSK of power limited military GEO comsats, and for space science missions like NEARS. Current program targets for first application include both a commercial technology demonstration spacecraft and a military application. The LPATs program will demonstrate flight-type (0.5 kW, 450 - 500 second Isp) hardware in the 1996/1997 timeframe. The OBP program also sponsors research on the feasibility sub-0.25 kW arcjets for very small spacecraft (Ref. 15).

Electrostatic Systems

The major electrostatic concepts include both gridded ion and Hall effect thrusters. As noted, gridded ion thruster technology previously sponsored by the OBP program is now the subject of focused development. Currently, several cooperative programs to evaluate Hall thrusters for low power (sub-2 kW) applications are supported. Both higher power/performance Hall and next generation gridded ion technologies are being examined for future high delta-V missions. Over the next year, the OBP will also initiate an effort to evaluate the fundamental feasibility of a micro-electrostatic system (sub-0.1 kW) for microspacecraft missions.

Hall thrusters have been extensively developed in Russia (Ref. 16) and have been an area of significant interest in the western aerospace community over the past several years. Two variations exist, the stationary plasma thruster (SPT) and the thruster with anode layer (TAL). Demonstrated performance characteristics are similar for both devices. For the kW-class, demonstrated specific impulse for both devices is on the order of 1600 s at 0.50 efficiency. Both 0.7 kW and 1.5 kW SPT's made by Fakel Enterprises are operational on Russian satellites and the 1.5

kW version is now being readied for commercial use on western commercial GEO comsats (Ref. 4). Extended, cyclic life (>6000 hours/5000 cycles) was recently demonstrated for the 1.5 kW thruster (Ref. 17) and extensive evaluations of integration impacts have been undertaken including several large scale tests in OBP testbeds in cooperation with industry (see, for example, Ref. 18).

Over the past several years, the OBP has acted as an agent for the Ballistic Missile Defense Organization's (BMDO) electric propulsion program. At present, this program is focused on the development of an advanced 1.5 kW Hall thruster system "on-a-pallet" in the Russian Hall Effect Thruster Test program (RHETT - see Refs. 19, 20), and OBP personnel manage this effort. The first flight-like package (RHETT-1, shown in Figure 9) will be demonstrated in ground testing in 1995 and a follow on, flight-ready system (RHETT-2) is planned for a near term flight test.

Sub-kW Hall thrusters are being considered for several missions including space science. One high potential mission prospect is the Energetic Transient Array (ETA) mission now being developed in a Phase A study by the Massachusetts Institute of Technology in NASA's MIDEX program. In ETA, eight small spacecraft would be distributed in heliocentric orbit to locate gamma ray sources as a follow on to the Gamma Ray Observatory. Existing SPT thrusters, built by Fakel and supplied by the Air Force Phillips Laboratory, are baselined for spacecraft insertions. The OBP program will provide support to the ETA program (under a Space Act Agreement) in the form of extensive propulsion system demonstrations in ETA's ground test element.

Sub-0.5 kW Hall thrusters may offer very high performance levels for power limited applications but have not yet been demonstrated. The OBP program is currently supporting development/evaluation of two low power Hall technologies. One of these, a 0.5 kW-class TAL, was built by Russia's Central Research Institute of Machine Building (TsNIIMASH), through Texas Tech University, and will shortly be delivered for testing. Similarly, the Moscow Aviation Institute, through the Atlantic Research Corporation, will provide a 0.25 kW SPT thruster. Both of these Hall thrusters are engineering models and will be evaluated (performance, life, and integration impacts) in 1995 and 1996. Further development efforts will hinge on the outcome of this research.

For the far term (5 to 10 years), the OBP program has initiated efforts to develop a very high efficiency (> 0.6), low-mass plasma propulsion system with end-to-end system specific mass (including power) and lifetime goals of 10 kg/kW and 15,000 hours, respectively. These attributes are specified in the integrated Space Power and Propulsion Strategic plan (Ref. 5) and will enable 1) three to five year trip times for complex space science missions with small spacecraft and 2) electric orbit transfers (LEO to GEO-class) with high payload fractions and relatively short trip times (sub-3 month). At least two electrostatic concepts, an advanced gridded ion system and a high power (> 5 kW) Hall thruster-based system, will be considered. For the gridded concept, several potential grid technology options will be explored for high thrust density applications. Carbon-carbon grid technology (see, for example, Ref. 21) developed under OSAT's Advanced Concepts Program has shown great promise for reducing grid erosion and this technology is currently being transitioned to the OBP program. Several promising coatings for conventional molybdenum grids are also being examined. Some initial evaluations of high power Hall technology have been initiated in conjuction with the BMDO program (see, for example, Ref. 22). Low-mass power systems for these advanced concepts will incorporate new high voltage array, power conversion, and power distribution technologies and efforts are underway, with the OSAT Space Power program, to demonstrate advanced power system concepts (Ref 23).

Electromagnetic Systems

For many years the magnetoplasmadynamic thruster (MPD) was the major focus of OBP efforts in the electromagnetic regime. Because of their large power handling capabilities and projected high performance, MPD systems were considered prime candidates for very ambitious, high power missions such as those proposed for the Space Exploration Initiative. The recent trend toward small satellites relegates MPD research to the back burner and the OBP retains only a minor effort to examine the feasibility of MPD thrusters for dual use applications such as plasma processing/manufacturing. Pulsed plasma thrusters (PPT) are now the focus of the OBP electromagnetic element for several reasons. These devices utilize solid propellant and provide over 1000 s of specific impulse while operating at power levels between 2 and 60 watts. Because the systems are pulsed, power throttling can be easily accomplished without changing performance by varying repetition rate. Impulse bits at least three orders of magnitude below those available with hydrazine engines (13 mN-s) can be

used to provide fine orbit control. The use of solid fluoropolymer propellant eliminates hazardous propellant storage and handling concerns and results in a very simple, low-cost feed system. These attributes make PPTs highly attractive for a range of small spacecraft applications. The OBP program is now in the middle of a two phase PPT technology development effort which includes in-house, contracted, and university efforts. The first phase is focused on simultaneously reducing the PPT system mass by a factor of two and doubling total impulse capability in order to provide a four fold increase in propulsion system capability per unit launch mass as compared to SOP PPT systems. The second phase will further miniaturize the technology and fundamental research efforts toward this end are already in progress. In the contracted effort, the Olin Aerospace Company will first develop a flight-type system for demonstration in 1997. The in-house program is focused on the characterization of performance, EMI, and plume impacts. The academic effort, conducted with the Ohio State University (OSU), is building on past code development efforts (MACH 2 - Ref. 24) to develop a high fidelity PPT model to be used in the design of next generation PPT's. OSU is also exploring new propellant options for increasing PPT performance without degrading life (Ref. 25). To date, layered polymer combinations that provide higher average specific impulse characteristics but avoid electrode carbonization problems encountered in previous advanced fuel development efforts are being tested. All of the on-going PPT efforts take advantage of existing OBP testbeds. Recent program outputs include

1) development and demonstration of a new power converter providing significant reductions in volume (3X), weight (2X), parts count (4X), and power consumption (3.5X) over SOP systems,

2) development and demonstration of a telemetry board providing a 4X reductions in volume, weight, parts count, and power consumption over SOP,

3) identification and testing of 2 candidate capacitor technologies with 4X the specific energy density of SOP technology, and

3) Development and demonstration of a high precision PPT thrust stand (Ref. 26).

As a final note, the OBP is working cooperatively with the Air Force and Webber State University in the joint Air Force/Webber State student satellite project (JAWSAT). JAWSAT will fly SOP LES 8/9 PPT technology on a 50 kg educational smallsat which will use the Global Positioning System (GPS) for navigation. Under this program, OBP personnel are conducting and directing tests in LeRC space propulsion testbeds to quantify and address issues related to PPT/spacecraft integration as illustrated in Figure 10. Figure 10(a) shows two students preparing JAWSAT for a test to examine the impacts of PPT system EMI on other spacecraft systems in a vacuum chamber at LeRC. Another test of the PPT was recently performed using a small, portable non-conductive vacuum facility, Figure 10(b), to show that PPT firings did not adversly impact the GPS downlink. Programs such as JAWSAT provide educational opportunities for students and OBP personnel alike and valuable information on spacecraft integration to be used in the development of next generation systems.

CONCLUDING REMARKS

On-Board propulsion is a major mission performance driver for a broad range of space applications. Known and anticipated mission requirements will require the use of innovative new electric propulsion systems in both the near- and far-term. To meet these national requirements, NASA's Office of Space Access and Technology (OSAT) sponsors an aggressive on-board propulsion R&D program (OBP) which includes a strong electric propulsion element. Synergistic space power technologies are address in a complementary OSAT program. These OBP programs stress technology transfer and program efforts are directed toward the development of commercial technology sources and the demonstration of program technologies to the level required by potential users. The On-Board Propulsion program is committed to providing cutting edge electric propulsion technologies to the aerospace community and invites interactions with the community to help meet this goal.

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Table 1. Emerging Technology Drivers.

- Smaller Spacecraft and Launch Vehicles
- Multiple Deployments per Launch
- Increased Payload Mass/Life
- Reposition and Precision Positioning
- Deorbit Policy
- Reduced Infrastructure and Operations

Table 2. Anticipated On-Board Propulsion Trends.

FUNCTION	LEO/MEO	GEO	SPACE SCIENCE
• INSERTION	● → ○/□	● → ○/□	● → ○/□
• ORBIT CONTROL	●/□ → ○/□	●/■ → ○/□	● → □
• REPOSITIONING	● → ○/□	● → □	● → □
• DEORBIT	● → ○/□	N/A	N/A
• SAMPLE/RETURN	N/A	N/A	● → ○/□

○ - CHEMICAL; □ - ELECTRIC
CLOSED SYMBOLS - SOA; OPEN SYMBOLS - ANTICIPATED TRENDS

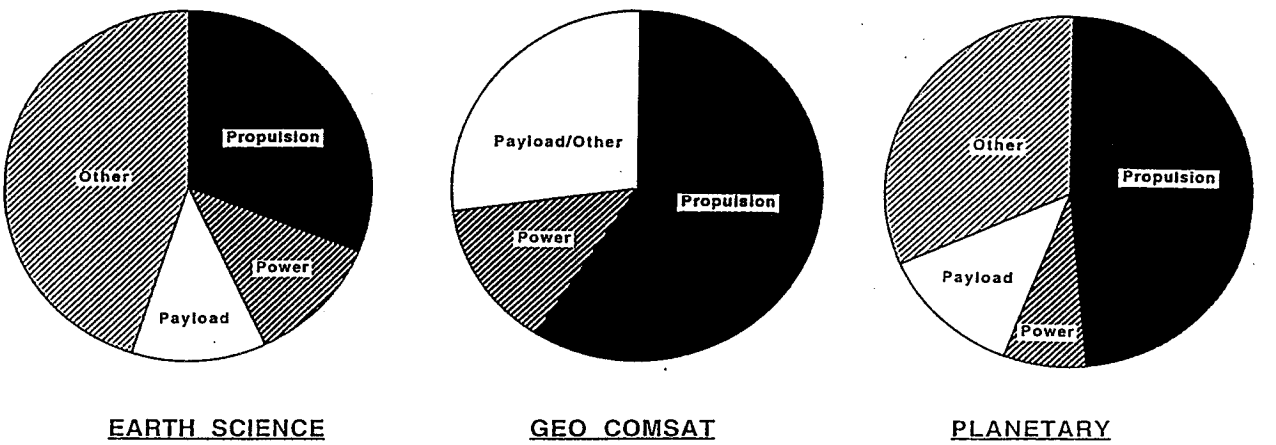


Figure 1. Spacecraft wet mass fractions for Earth-orbit and planetary missions.

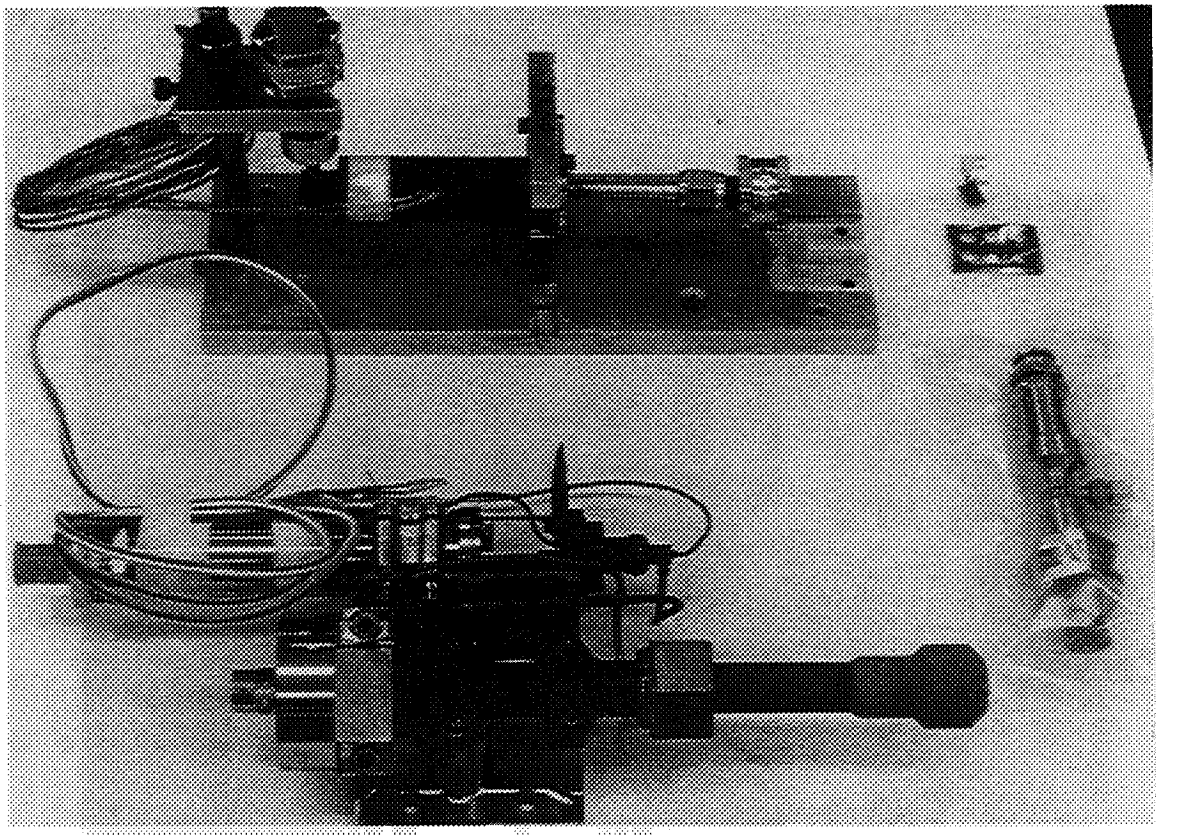
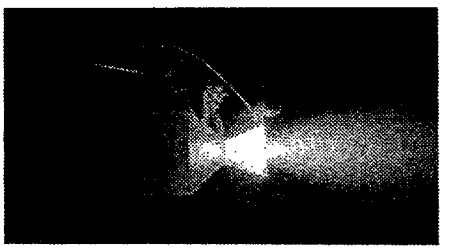


Figure 2. High performance (600 s Isp) arcjets for next generation communications satellites.

ELECTROTHERMAL

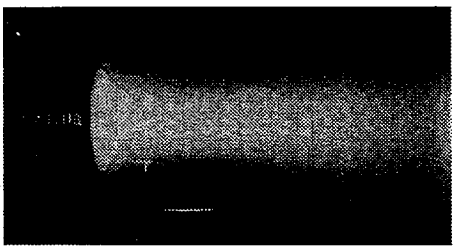
- GAS HEATED VIA RESISTANCE ELEMENT OR ARC AND EXPANDED THROUGH NOZZLE



- RESISTOJETS
- ARCJETS

ELECTROSTATIC

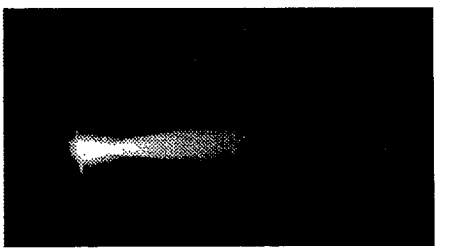
- IONS ELECTROSTATICALLY ACCELERATED



- ION
- HALL

ELECTROMAGNETIC

- PLASMA ACCELERATED INTERACTION OF CURRENT AND MAGNETIC FIELD



- PPT
- MPD

Figure 3. Electric propulsion classes.

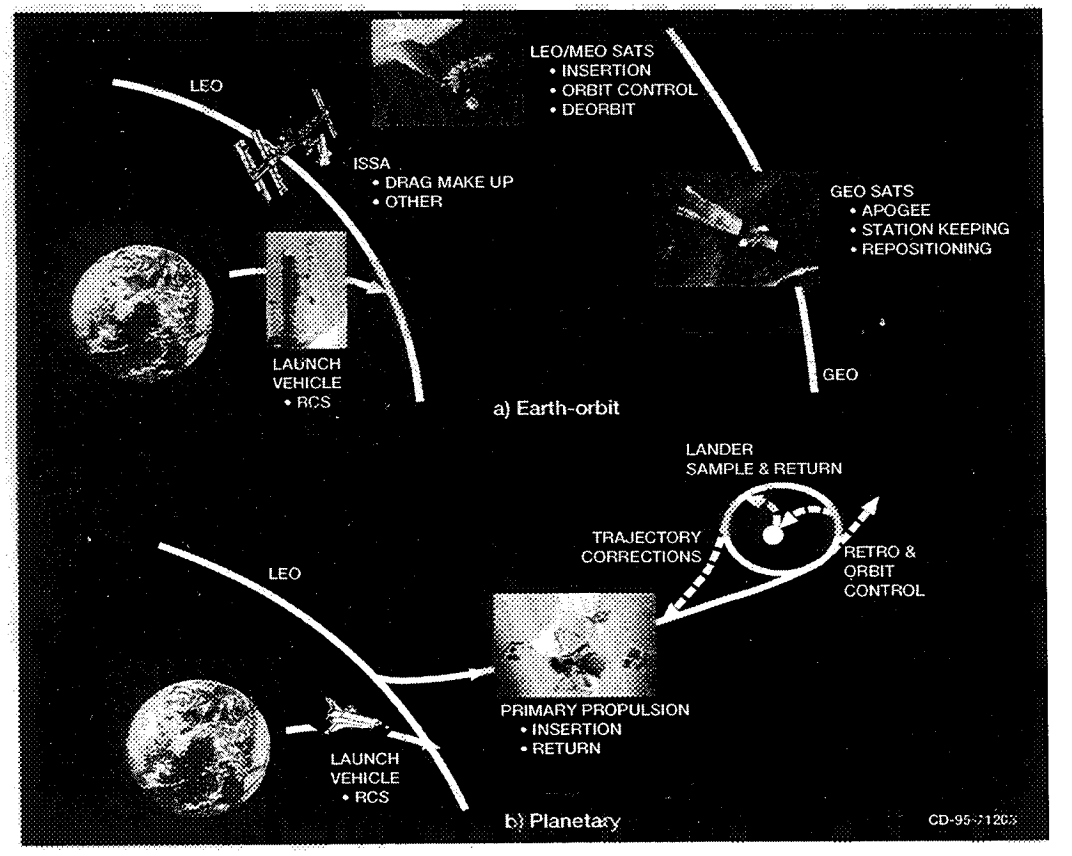


Figure 4. Earth-orbit and planetary mission propulsion functions.

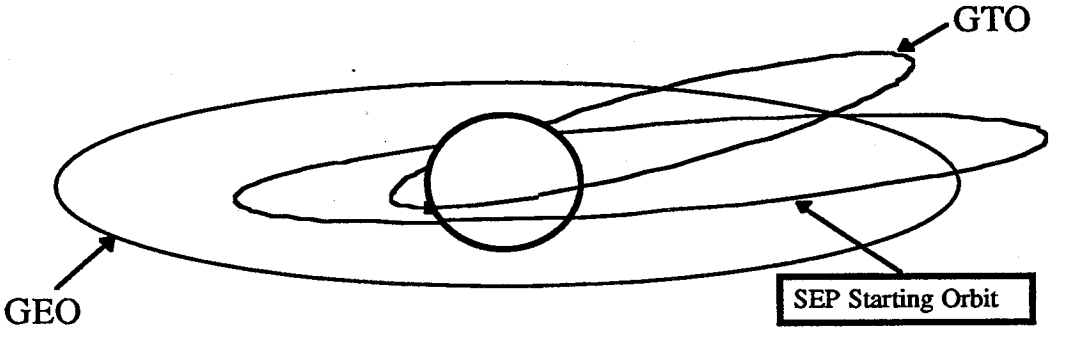


Figure 5. Near-term electric propulsion orbit insertion strategy for GEO comsats.

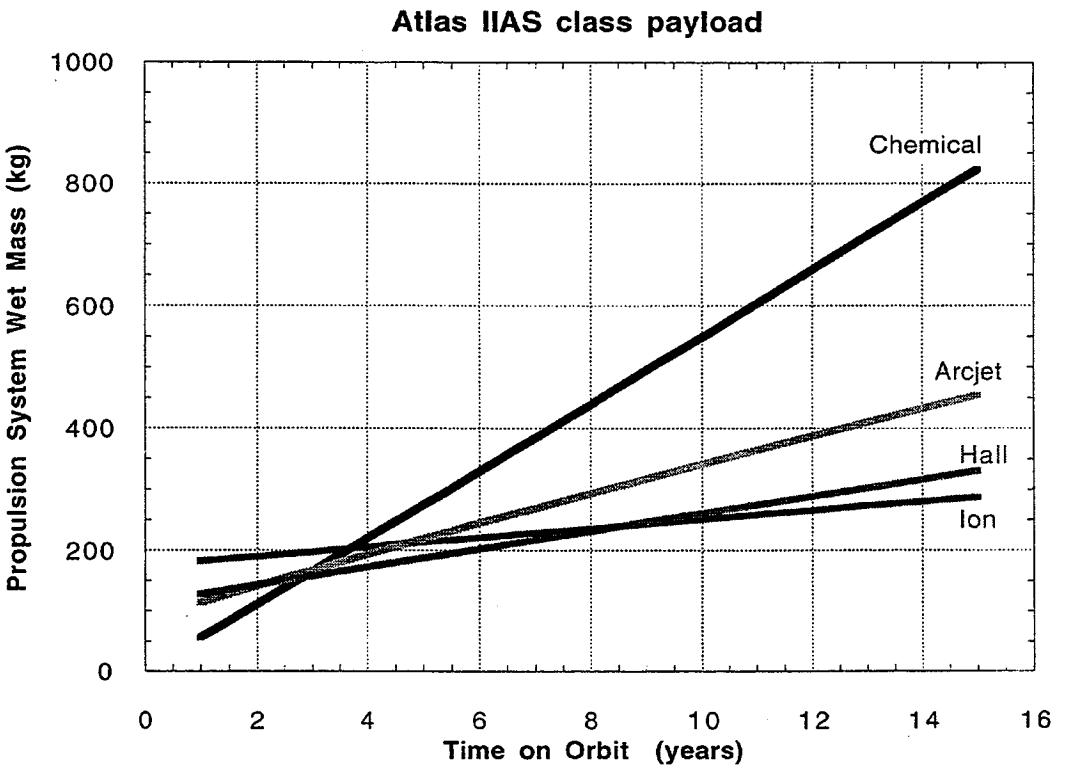
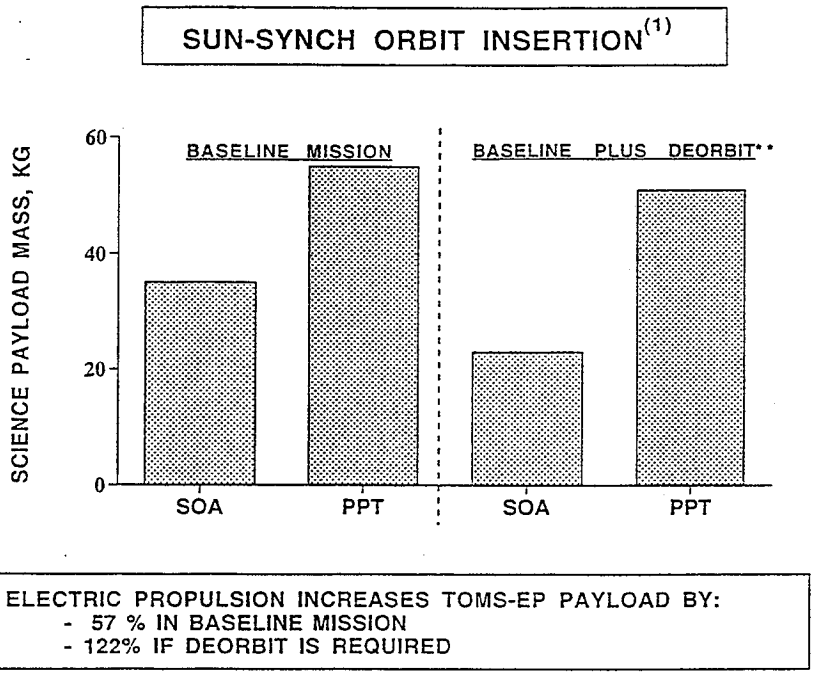


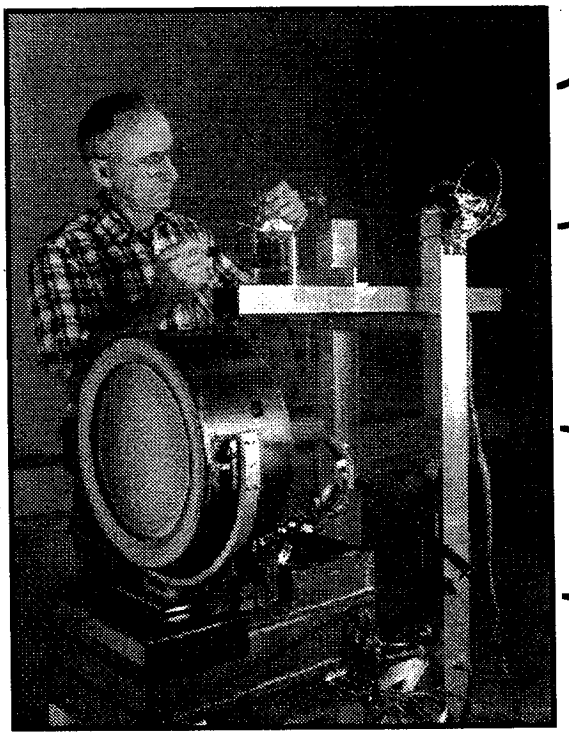
Figure 6. Propulsion system wet mass versus time on orbit for an Atlas 2AS-class GEO comsat with various propulsion options for NSSK/repositioning.



(1) TOMS-EP MISSION, LAUNCH MASS OF 287 KG, FINAL ORBIT ALTITUDE OF 955 KM, 80 DAY INSERTION
** DEORBIT TO 500 KM.

Figure 7. Electric propulsion benefits for an Earth science mission (TOMS example).

PROGRAM DIRECTIONS - ELECTRIC



PULSED PLASMA THRUSTERS
- LEO/MEO INSERTION, MAINTENANCE, DEORBIT
- PRECISION POSITIONING & ACS

ARCJETS/HALL THRUSTERS
- LEO/MEO INSERTION, MAINTENANCE, DEORBIT
- GEO NSSK FOR POWER LIMITED COMSATS
- APOGEE TOPPING
- MODERTE ΔV SPACE SCIENCE

NEXT GENERATION PLASMA THRUSTERS
- HIGH ΔV ORBIT TRANSFERS & SPACE SCIENCE
- NSSK & REPOSITIONING

MICROTHRUSTERS FOR SUB-10 kg SPACECRAFT

Figure 8. Near-term electric propulsion thrust areas.

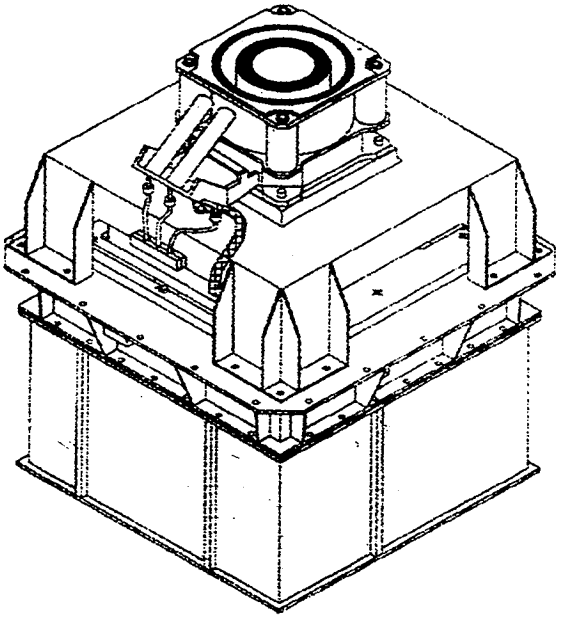


Figure 9. RHETT-1 demonstration package.

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

Most space missions require on-board propulsion systems and these systems are often dominant spacecraft mass drivers. Presently, on-board systems account for more than half the injected mass for commercial communications systems and even greater mass fractions for ambitious planetary missions. Anticipated trends toward the use of both smaller spacecraft and launch vehicles will likely increase pressure on the performance of on-board propulsion systems. The acceptance of arcjet thrusters for operational use on commercial communications satellites ushered in a new era in on-board propulsion and exponential growth of electric propulsion across a broad spectrum of missions is anticipated. NASA recognizes the benefits of advanced propulsion and NASA's Office of Space Access and Technology supports an aggressive On-Board Propulsion program, including a strong electric propulsion element, to assure the availability of high performance propulsion systems to meet the goals of the ambitious missions envisioned in the next two decades. The program scope ranges from fundamental research for future generation systems through specific insertion efforts aimed at near term technology transfer. The On-Board propulsion program is committed to carrying technologies to levels required for customer acceptance and emphasizes direct interactions with the user community and the development of commercial sources. This paper provides a discussion of anticipated missions, propulsion functions, and electric propulsion impacts followed by an overview of the electric propulsion element of the NASA On-Board Propulsion program.

14. SUBJECT TERMS

Electric propulsion; On-board propulsion; Spacecraft propulsion

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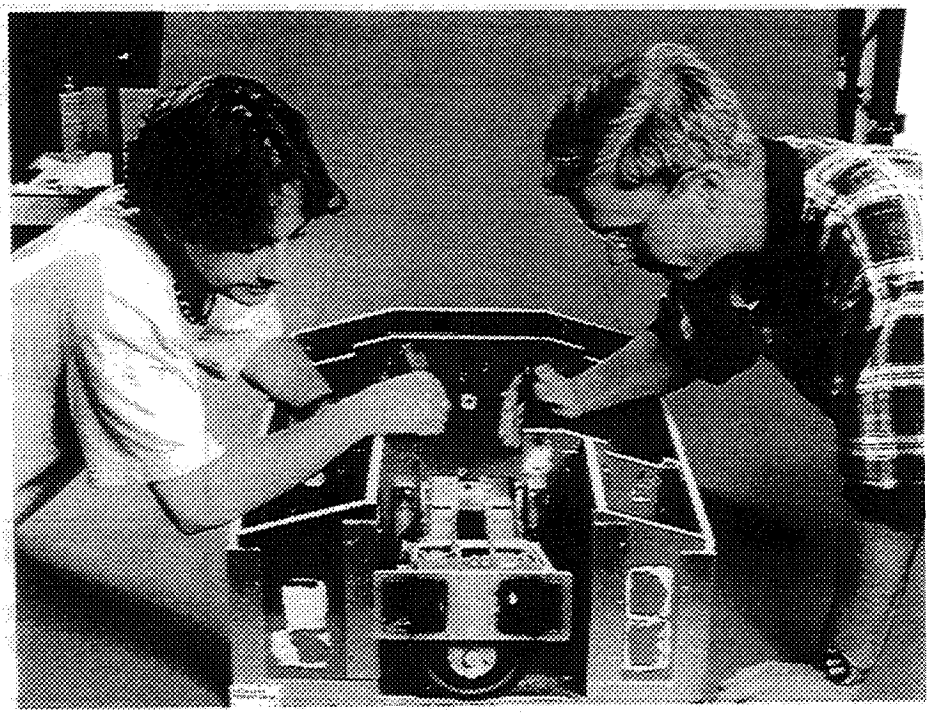
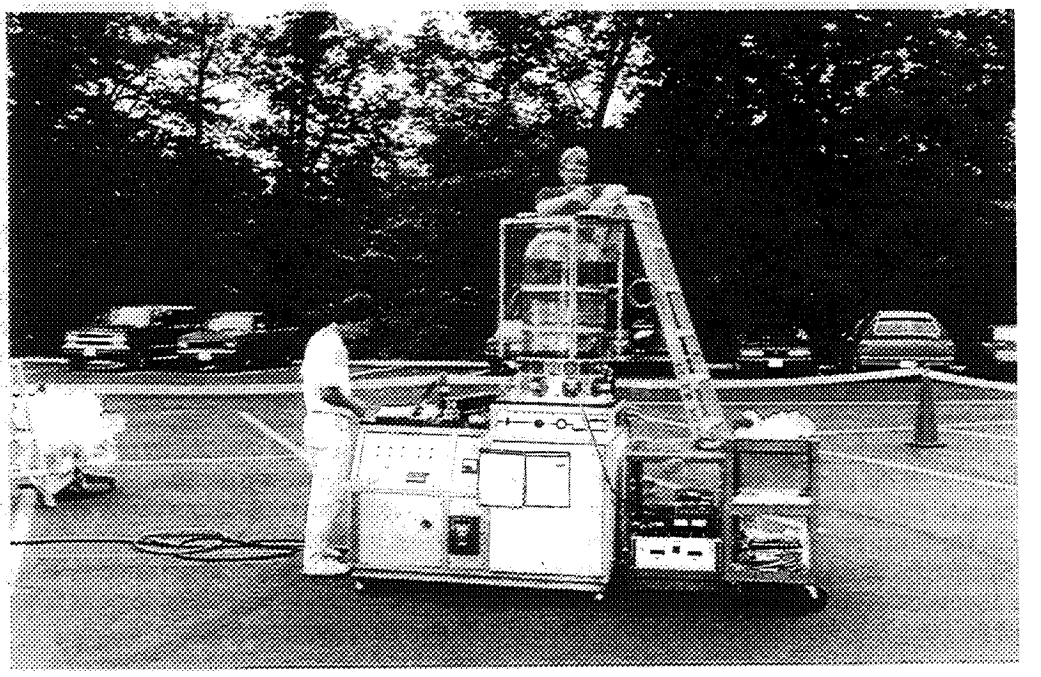


a) Students preparing JAWSAT for PPT integration impacts testing.



b) Tests of PPT impacts on GPS downlink for JAWSAT program.

Figure 10. Pulsed plasma thruster program examples.