Paper Session II-B - The Electric Insertion Transfer Experiment (ELITE): An Air Force Critical Experiment to Revolutionize Space Transportation

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An Air Force Critical Experiment to Revolutionize Space Transportation

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ABSTRACT

As the Air Force mission in space continues to expand, the cost of delivering the necessary resources to assure mission accomplishment has become a critical issue. With the amount of payload delivered to high earth orbit driven by the characteristics of the upper stage, significant benefits can be achieved by reducing its weight and/or increasing its performance. Highly efficient electric propulsion stages can provide advantages in both areas. Ongoing studies at Air Force Space Command and Space Systems Division have identified some payoffs of using this revolutionary propulsion method to power future orbit transfer vehicles. Preliminary results indicate that an Electric Orbital Transfer Vehicle (EOTV) may allow us to efficiently launch some of our largest payloads, currently planned for Titan IV, on Atlas or Delta class vehicles. This capability offers the potential to significantly reduce launch costs by tens of millions of dollars per mission. The Electric Insertion Transfer Experiment (ELITE) is proposed as a "critical experiment" to demonstrate the capability of solar electric propulsion in an orbit raising mode.

ELITE integrates several ongoing technology programs within the Department of Defense (DoD) and NASA in a space demonstration. The experiment will address issues associated with low thrust, solar powered orbit transfers and methods for autonomous control of EOTVs. ELITE will also address issues peculiar to electric thrusters such as contamination of spacecraft components, plume-plume interaction of multiple thrusters, charging of spacecraft surfaces and potential interference with radio frequency transmissions and other electronics. Other potential applications for electric propulsion are also discussed in the context of future DoD and NASA missions.
INTRODUCTION

DoD Space Policy directs that assured mission capability be maintained through complementary strategies of assured access to space, robust control and asset survivability. The policy also directs pursuit of transportation concepts that significantly reduce cost while improving capability, availability and flexibility. The Air Force has reconstituted the Expendable Launch Vehicle (ELV) base to assure access to space for the warfighters. The objective of the Advanced Launch System (ALS) and National AeroSpace Plane (NASP) programs now underway, is to provide cost effective transportation to Low Earth Orbit (LEO). The final leg of the space transportation sortie is moving the satellite from LEO to its destination orbit. Although current Air Force Space Command (AFSPACECOM) Military Advanced Launch System requirements1 address the launch vehicle segment of the space transportation mission, the orbit transfer vehicle(OTV) portion is still being studied.

In the same way that our current tactical and strategic forces are deployed in a wide variety of places with each group having its own unique function and mission, our satellite constellations reside in a large array of orbits from low earth to geosynchronous. Once our satellites are delivered into parking orbit, they are transferred to their destination using chemical propulsion stages like the Inertial Upper Stage (IUS) and Centaur. These chemical stages are complex, very costly and require time consuming operations before launch. Revolutionary methods to reduce costs to deploy our resources in space more efficiently must be developed now.

At the Astronautics Laboratory ongoing efforts, part of the Advanced Orbit Transfer Vehicle Study, have focused projected OTV requirements into three categories: present capability, near term (1990-2000), and far term (2000+). Present capability includes both liquid and solid fueled chemical systems. Far term concepts include solar and nuclear propulsion systems. The only near term OTV concepts that can significantly improve capability and save costs are solar electric propulsion based. These systems are referred to as Electric Orbit Transfer Vehicles or EOTVs. EOTVs will provide Air Force and Unified Space Command operational commanders with the ability to launch payloads which now require Titan IV boosters on smaller and less expensive Medium Launch Vehicles (MLV). Current economic analyses indicate the potential to save hundreds of millions of dollars by remanifesting these payloads on MLVs2,3. Using EOTVs will also significantly increase payload capability and allow multiple satellite launches on one booster3. Figure 1 illustrates the relative advantages of the two most promising electric propulsion concepts as compared with chemical systems.
High performance electric propulsion will also increase satellite availability if the weight savings enabled by the use of electric propulsion systems are used to provide additional propellant and thus extending the lifetime of the satellites.

By virtue of its need to continuously thrust at low levels, the EOTV/satellite system will be changing its ephemeris continuously. Studies to evaluate the capability to enhance survivability by incorporating these EOTV characteristics are ongoing.

To take advantage of these tremendous payoffs AFSPACECOM is currently reevaluating the way space resources are deployed. Because of their low thrust, transfers which take hours on the IUS will take weeks to months on an EOTV. Thus the deployment timeline of a satellite constellation must account for this transit period.

THE ELECTRIC INSERTION TRANSFER EXPERIMENT (ELITE)

Electric propulsion has been under investigation for over two decades. In the 1960's there was a significant effort underway to develop nuclear power for space. Electric propulsion, being power hungry, was a natural complement but the technology push subsided with the demise of the reactor programs. Today, advances in lightweight solar power makes the consideration of solar EOTVs practical. To capitalize on this opportunity, technologists are collaborating within Air Force, NASA and the SDI organizations and have defined a program initiative for a
cooperative space experiment called the ELectric Insertion Transfer Experiment (ELITE).

Although participation by all interested agencies is desired, ELITE is an Air Force "critical experiment" whose primary objective is to demonstrate the capability of solar electric propulsion in an orbit raising mode.

ELITE represents a tremendous opportunity to demonstrate mission enabling and mission enhancing capabilities using solar electric propulsion. Proposed for launch in late 1995, ELITE will provide a testbed to integrate the technologies necessary for operational application of EOTVs. These technologies include electric thruster systems; large, lightweight power systems; and autonomous flight control algorithms.

ELITE SUBSYSTEM DESCRIPTIONS AND TECHNOLOGY STATUS

Electric Propulsion Technology

The two electric propulsion technologies which are mature enough to be considered for an operational orbit transfer vehicle are the arcjet and ion thruster systems. Exploratory development of a third electric propulsion concept called the Magnetoplasmadynamic (MPD) thruster is underway. This propulsion concept holds great promise for future advanced EOTVs because it combines the advantages of both the arcjet and ion systems. The MPD devices provide the high Isp of the ion engines while operating at a thrust level roughly equivalent to the arcjet system. The current state of development of the arcjet and ion systems are discussed in the following paragraphs.

Arcjet Technology

An arcjet is a relatively simple, compact electrothermal propulsion device which can process tens of kilowatts of power. These thrusters have demonstrated the ability to operate over a wide range of power settings. The current high power 30kW device has been tested from 10 to 100 percent of its rated level. This characteristic may provide the flexibility necessary to compensate for graceful degradation of the EOTV system as the power generation capability of its solar arrays degrades with residence time in the Van Allen radiation belts.

Arcjets operate by flowing propellant, usually ammonia or hydrazine, around and through an electrical arc. The arc heats the propellant which is then expanded in a nozzle. The only difference between an arcjet and a chemical rocket engine is the manner in which
the propellant is heated. The propellant flow is directed to protect the thruster from the arc. This enables the thruster to operate with bulk propellant temperatures of tens of thousands of degrees, corresponding to 800 seconds or greater specific impulse. This performance is two to three times the specific impulse performance of the current chemical systems. The IUS and Centaur OTVs have Isps on the order of 280 and 430 sec, respectively. The thrust produced by the arcjet is on the order of 0.015 pounds per kilowatt of power, which is orders of magnitude lower than current chemical stages.

Both low (1-5 kW) and high power (26-30 kW) arcjet subsystems are currently being developed. The subsystems include the thruster, power conditioning unit and propellant feed system. Low power subsystems in the 1-2 and 2-5 kW power range, developed utilizing hardware designed under NASA/LeRC sponsorship and are currently undergoing flight qualification for launch in 1992. The 1.3 kW device developed by NASA/LeRC has been chosen by General Electric as the operational North/South stationkeeping system for a new series of commercial satellites starting with the AT & T Telstar IV program.

Other programs include the Astronautics Laboratory sponsored 30 kW Arcjet Advanced Technology Development program and the SDIO sponsored SP-100 30 kW Arcjet Mission Development program which is ongoing at JPL with TRW and General Electric. The AL program will provide a complete, flight qualified subsystem for launch in the mid 1990's. Additionally, the AL is sponsoring the High Power Arcjet Endurance Test. The development of a high power Power Conditioning Unit (PCU) is being sponsored at Space Power Incorporated by the SDIO Innovative Science and Technology Office under a Small Business Innovative Research (SBIR) program.

Ion Subsystem

Ion engines are somewhat more complex, large electrostatic acceleration devices. These systems offer the highest specific impulse currently available. In the body of an ion engine, a gas, typically very low pressure xenon or krypton, is exposed to a flow of electrons which ionize the gas' atoms. These ionized atoms then drift between two electrically charged grid electrodes at one end of the thruster. These charged grids are arranged to use the principle that like charges repel and opposite charges attract, to accelerate these ions to very high velocities yielding specific impulses of several thousands of seconds. The ion engines create thrust forces an order of magnitude lower than the arcjets and therefore trip times for the same payload mass will be concomitantly longer.
Development of 5-10 kW ion thrusters is currently sponsored by both NASA/LeRC and the UK Royal Aerospace Establishment\textsuperscript{4}. The RAE, Farnborough is developing the 10 mN Power Conditioning and Control Equipment (PCCE) for the UK-10 system and the cathode for the UK-25 thruster. The UKAEA Culham Laboratory is responsible for testing both thrusters and constructing of the UK-25. Marconi Space Systems Ltd. is developing the Propellant Supply and Monitoring Equipment (PSME) and 25 mN PCCE for the UK-10 ion propulsion system. They are also performing studies of applications to various spacecraft, including Intelsat 7 and ESA's proposed experimental communications satellite, SAT-2.

Previously, 30 cm mercury ion thrusters baselined at 2.6 kW for the NASA Solar Electric Propulsion System (SEPS) were operated with xenon propellant up to 20 kW. Presently, thrusters incorporating the ring-cusp design are recommended. These thrusters have been operated to power levels of 11-15 kW. A laboratory model has been operated at levels greater than 5 kW for over 300 hours.

Lightweight Power Systems

One of the key technological advancements making the consideration of EOTV's practical is lightweight, radiation hardened solar arrays. Since operational EOTV's will require over 40 kW of power, conventional arrays would not be acceptable. The Jet Propulsion Laboratory has been developing the Advanced Photovoltaic Solar Array (APSA). These arrays are roll-out/fold-out types that can be stowed in a small volume. They will incorporate Gallium Arsenide solar cells to enhance survivability of the array during transfer through the Van Allen radiation belts.

In the mid 1980's NASA demonstrated an earlier lightweight solar array concept in a Shuttle experiment known as the Solar Array Flight Experiment. A 100 foot long array was deployed and retracted several times providing valuable data applicable to the APSA effort.

Autonomous Flight Control

EOTVs create unique demands on the guidance, navigation and control system. Dynamics of the constantly thrusting vehicle may require performance of "snap roll" maneuvers. A requirement for new attitude control components, such as thrusters and reaction wheels, will not be required for an EOTV. If we assume that the economically attractive launch-on-schedule philosophy of space transportation is adopted by the Air Force, then the vision of a "pipeline convoy" of satellites in transit to their destination orbits will become a reality. The cost implications of a
standing army of controllers monitoring these vehicles may be significant. Therefore there is a real need to develop the logic and software algorithms to autonomously control the satellites with minimal human supervision during the long spiral transfer.

There are current Air Force sponsored efforts ongoing with the Irvine Technology Group\(^5\) and others under the Small Business Innovative Research Program that address autonomous flight management for low-thrust orbit transfer.

Diagnostics

The most critical issues which will need to be resolved by the ELITE are those associated with determining the ambient and induced environments to which the EOTV payload (spacecraft) will be subjected. Potential space transportation service users will need to understand this environment to evaluate its impact on the spacecraft’s mission capability and operational lifetime. Diagnostics will be placed on board the ELITE to ensure that the appropriate data is available to make these evaluations.

The diagnostics package will consist of a wide array of sensors and instrumentation to gather required data. The ELITE mission cannot encompass all possible environmental conditions. It is critical that a comparison between predicted and actual performance be made so that future missions can make use of computer simulated mission parameters with confidence. Contaminant deposition will be measured. Some of the specific instruments to be used include: Mass spectrometer, optical spectrometer, Langmuir probes, quartz crystal microbalances, and cameras\(^6\).

ELITE DEMONSTRATION OBJECTIVES

The ELITE mission will address a wide array of system and subsystem issues associated with EOTV space operation. Since the presence of gravity and lack of accurate environmental simulation facilities can significantly affect many of the subsystems and components associated with an EOTV, the emphasis will be on those issues which can only be answered with an on-orbit test.

The issues discussed in the previous section on spacecraft ambient and induced environments and autonomous flight control are two of the most critical concerns and can only be fully addressed through an on-orbit demonstration.

Electric propulsion performance has been demonstrated on the ground in vacuum chamber conditions. However, it must be shown that
the hardware can deliver the thrust and specific impulse required when integrated with other spacecraft subsystems in a harsh radiation environment. Also, there is some concern as to the possibility of electromagnetic interference and spacecraft charging from the operation of the thrusters.

The large flexible solar arrays will greatly impact dynamic characteristics of the satellite and methods for control will be incorporated and demonstrated. Also, radiation is expected to significantly degrade array power output and this must be verified to determine the effect on propulsion system performance and to derive future oversizing requirements.

Figure 2 illustrates a conceptual ELITE spacecraft with the major subsystems highlighted.

Figure 2. Conceptual ELITE Spacecraft
BASELINE MISSION SCENARIO

The baseline flight profile for the ELITE mission allows for launch from either the Eastern Test Range or the Western Test Range. The estimated total weight of the spacecraft will be low enough to allow for launch on a medium launch vehicle class or a standard small launch vehicle class booster. From a parking orbit of approximately 200 nautical miles the ELITE spacecraft will be deployed and checked out. This minimum altitude is important because the large solar arrays are subject to unacceptable drag forces at lower altitudes. After initialization of the guidance system and diagnostics, the vehicle begins its 3-6 month transfer into the Van Allen radiation belts. This transfer includes both altitude and inclination changes. The mission is designed to demonstrate sufficient EOTV operation for a full scale engineering development program to commence at completion of the experiment. Acquired data will be downlinked for reduction and analysis by the ELITE team. Total on-orbit mission duration is approximately 6-9 months. The spacecraft will still be "alive" after the completion of the ELITE mission and can support other on-board experiments for a period much greater than 9 months.

PROGRAM SCHEDULE

The program has been divided into several phases. Due to the budget cycle, the major design and integration activity will begin at the beginning of fiscal year 1992. Prior to that time, the Astronautics Laboratory and its team members are conducting systems engineering and mission analyses, to define a preliminary system. The ELITE program office is supplementing ongoing technology programs to assure the availability of highly reliable hardware when needed.

Figure 3 shows the major program phases which culminate with the flight in late fiscal year 1995.
CONCLUSIONS

ELITE is intended to be a proof of principle for Air Force OTVs of the future. NASA's Solar Exploration Subcommittee has identified solar and nuclear electric propulsion vehicles as both enhancing and enabling for 6 of the 12 priority missions in its development queue. Highly efficient and cost effective electric propulsion concepts will be critical for future Lunar and Martian initiatives because of their ability to move large masses in cislunar and solar space. The ELITE will put to rest the remaining issues associated with these technologies and pave the way for the next generation of orbit transfer vehicles and interplanetary probes.

REFERENCES