ELECTRIC PROPULSION: IMPLEMENTATION ISSUES

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ABSTRACT

An overview is given of the process and issues associated with implementing the various electric propulsion (EP) technologies on spacecraft for a range of missions from those currently operational to those high-energy exploratory missions coming into view. It is suggested that a clear, concise, and convincing package of information on EP mission utility, system benefits, spacecraft compatibility and subsystem readiness must be made available to mission planners and decision makers if the process of selecting EP for advanced missions is to be expedited. Also, because of the size and power requirements of EP systems for these missions, coordinated leadership and substantial developmental support will be needed in the immediate future.

I. INTRODUCTION

The electric propulsion community has spent many years promoting the use of EP with systems engineers, mission planners, spacecraft managers, user organizations, and governmental decision makers. Arguments using mission utility, benefit-to-cost ratio, spacecraft compatibility and development status in various combinations have not resulted in widespread acceptance for operational use. In addition, at the managerial level, there remains a significant lack of knowledge concerning EP technology and its utility, benefits and status.

A number of factors embedded in electric propulsion's history, in the United States at least, have contributed to this situation. Variable development support, changing emphasis among the various technologies within the EP field and missions that are proposed, supported, and then cancelled have all led to uneven progress. Another, possibly more significant factor, has been the elusive promise of sizable power sources that would match payload and propulsion needs on advanced spacecraft. The power gap was a major reason electric propulsion had been characterized in the past as the "technology of the future."

However, a conjunction of missions, power sources, and thruster systems is occurring that could see EP take its place as a major propulsion player in the planning and implementation of advanced missions. Also, because of a clear need for high performance propulsion systems, the realization is emerging among informed management that electric propulsion is an enabling technology for many energetic missions, particularly when seen from a system-level economic viewpoint.

National and regional planning toward space access and advanced technology development also indicates increased awareness of the utility of electric propulsion. This is particularly evident in the comprehensively planned and well-funded space program being carried out in Japan, where, for example, MPD technology has flown on the shuttle, mercury ion station keeping was flight tested on ETS-III, and, currently, a xenon ion system is undergoing qualification for operational north-south stationkeeping on the ETS-VI satellite.

With this as general background, the objectives of the present paper in its next sections are to define some of the issues that arise when implementing electric propulsion, provide an overview of pending EP missions, assess the status of various EP technologies in relation to the issues and missions, and suggest some lines of action. The observations and conclusions are necessarily based on the author's particular perspective and include some specific examples from experience with xenon ion systems for geostationary communication satellites.

II. IMPLEMENTATION ISSUES

The process whereby electric propulsion technology -- electrothermal, electrostatic, or electromagnetic -- evolves from concept to operational use can be summarized in many forms. One highly condensed outline is seen in Table 1, where those phases commonly experienced during most programs; feasibility, development, integration and operations have been included.

The early and middle stages of electric propulsion development are confined to solving material, design and operational problems, optimizing performance and refining hardware. As the technology and its designs mature, emphasis is shifted to defining operating modes and

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performance over a range of expected conditions while establishing life expectancy.

TABLE 1
EP IMPLEMENTATION

Phases	Illustrative Activities
1) Feasibility	• Concept Demonstrations • Subsystem Modeling • Experimental Correlations
2) Development	• Engineering Subsystem Refinement • Performance Mapping • Confirm Degradation Mechanisms • Life Capability Demonstration • Flight Type Hardware: Mfg/Test
3) Mission/Systems Studies	• Mission Utility • System Benefits • Spacecraft Compatibility • Subsystem Readiness
• Decision	• Technology Selection
4) Integration	• Integrated SC/EP Design • Detailed Functional, Interface & Operational Compatibility • Subsystem Flight Qualification
5) Flight Operations	• Performance Monitoring • Backup Demonstration • Automated Control Modes

In parallel, initial application studies frequently utilizing over-simplified and favorable assumptions provide an optimistic assessment of benefits in terms of mass savings, life extension, and operational and/or cost advantages. Finally, as the application studies become more realistic, the size of the benefits decrease somewhat, and practical details such as subsystem integration, plasma and ion beam interactions, orbital mechanics effects and power utilization come to the fore as a new set of "problems" to be dealt with.

The "third phase" in Table 1 which addresses mission and system issues, is included as a prerequisite before the decision point, a time period during which a particular EP technology would or would not be selected for spacecraft integration and oprational use. It is suggested that a comprehensive, condensed, clear, and convincing set of answers to the four issue areas must be assembled during the "third phase" and be made available to critical decision makers before EP can successfully pass the selection test.

The issues themselves are defined and grouped in an arbitrary fashion as seen in Table 2. They are defined in terms of studies that either need to be made, had been carried out during earlier phases, or can be answered by summarizing available experimental and analytical results.

TABLE 2
EP ISSUES

UTILITY——at the MISSION Level
- Technical and Operational Tradeoffs
- Primary and/or Auxiliary Roles

BENEFITS——at the SYSTEM Level
- Mass Savings Tradeoff:
  - — Increased Payload/Redundancy
  - — Extended Life
  - — Reduced Launches
  - — LV Flexibility
- Monetary Benefit/Cost Estimates

COMPATIBILITY——at the SPACECRAFT Level
- EP Configuration & Integration
- Power Supply, Interface & Control
- Thermal Dissipation & Temperature
- Plasma Plume Interactions
- Electromagnetic, Electrostatic & Magnetic

READINESS——at the SUBSYSTEM Level
- Development Maturity
- Production Hardware Capability
- Performance Repeatability
- Life Margin; Critical Components
- Integrated Subsystem Exeprience
- Qualification Test Assurance

Utility refers to the fundamental question of usefullness and compatibility of electric propulsion for a particular mission. Specific impulse, power-to-thrust ratio, thrusting time, required propellant mass, performance parameters and other EP subsystem characteristics are used as input to spacecraft configuration, mission, and operational trade-off studies. As the studies progress, EP and other competing propulsion options are compared in increasing detail at the mission level.

Once the basic utility of EP has been shown, a benefits "package" must be developed that analyzes benefits in all important monetary terms, establishing the technology as economically viable for the mission. The economic benefits arise to the first order from the increased specific impulse attainable with EP -- in some cases more than on order of magnitude over chemical systems. The mass savings that are realized, after deducting EP subsystem and added power system mass from the reduced propellant load, can be used to increase payload, reduce spacecraft mass, or extend life (i.e., increase ΔV) in various combinations. The mass, life, and capability benefits are then used during comparative estimates of development, fabrication, test, deployment and operational costs. In many cases, it is system level economics that show EP to be a mission-enabling technology.

As evidence of the viability of EP for a particular mission accumulates, the questions become more detailed, particularly with regard to compatibility of the EP subsystem with the spacecraft.

Table 2 lists a number of areas that are unique to electric propulsion because of the large amounts of power used relative to chemical systems and where energetic plasma beams can interact with the spacecraft directly or indirectly. The severity, means of controlling and, in case of electrostatic discharge phenomenon (ESD), the benefit of EP-spacecraft interactions have been discussed, analyzed and tested by many workers. A number of interactions associated with ion stationkeeping subsystems for communication satellites have been summarized by the author.[1]

A fourth issues area that requires a comprehensive, yet concise, body of convincing data is the readiness of a particular EP technology for final pre-flight development and qualification. That is, are theoretical models well in-hand; are life-limiting mechanisms known; can the transition from development hardware to production units be made while maintaining performance levels; does the design have adequate life margin beyond mission requirements; has sufficient experience been accumulated with full subsystem operation at the extremes of its performance evenlope; and can the subsystem in its spacecraft-integrated form be fully qualified with existing facilities? It is frequently the case that data and experience have been accumulated over fairly long periods using different hardware, various operating conditions, and different test facilities. This leads to a significant amount of technical rationalization, interpretation, and extrapolation being required for the development of a comprehensive picture of subsystem readiness.

Experienced managers, waiting to make a decision on one element of a highly complex spacecraft, have little time and less patience with incomplete and unconvincing arguments promoting a particular advanced technology.

III. MISSIONS OVERVIEW

Electric propulsion in all its electrothermal, electrostatic, and electromagnetic forms is currently under serious scrutiny for near, mid, and far-term application to a variety of missions, with both auxiliary and primary propulsion roles involved.

The purpose here is to illustrate the range of EP applications, either currently operational, firmly in hand or where EP is clearly a contender by providing an enabling solution to the propulsion problem. Also, a number of completed, schdeuled, and planned flight tests are cited whose success will contribute significnatly to EP's readiness image.

Table 3 provides an outline of the five mission categories where EP can be effectively employed. The figures cited below are selected examples of hardware or spacecraft that illustrate the different missions in the table.

TABLE 3
EP MISSIONS OVERVIEW

	Schedule				
	Current		Near Term	Future	
Mission	GEO Satellites	Space Station	Constellation Deployment	Lunar Base	Solar Exploration
Spacecraft	Commercial Com Sats	Large Platform	Satellite +EP Stage	Cargo +EP Stage	Large Multi-Stage Vehicle
Number	2 to 10 (Subsystems)	1 (+EP Replacements)	2 to 5 Multi use Stages	2 to 3 Multi-use Stages	1 to ? (Multiple EP Systems)
Propulsion Role	Auxiliary	Auxiliary	Primary	Primary	Primary
EP Function	Station Keeping	Drag Makeup	SDIO & GPS Orbit Transfer	Orbit Transfer	Mars Sample & Man Return
Power Source	Kilowatt Solar + Battery	Solar + Electro-Chemical	Large Solar/ Small Nuclear	Large Solar	Megawatt Nuclear

Fig. 1 shows electrothermal hydrazine thrusters (Rocket Research) for north-south stationkeeping, that have operated successfully for a number of years on several series of GE Astro Division communication satellites. Low-power thermal arcjets (≈1kWe) have also been under active development for follow-on performance improvement. An autonomous life test has been completed at NASA Lewis, and a flight demonstration is planned for such an arcjet system in 1990.

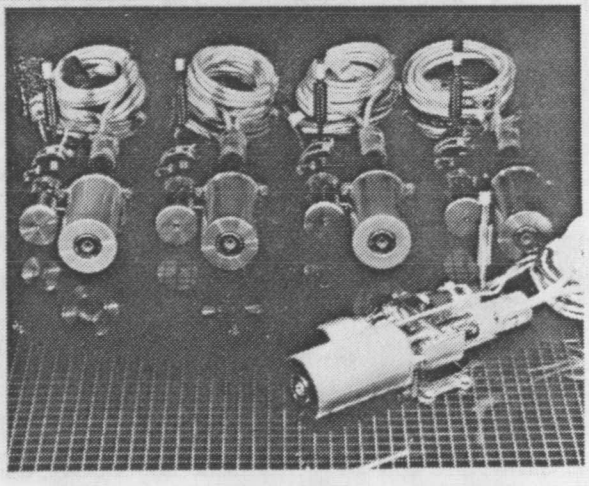

FIGURE 1
ELECTROTHERMAL HYDRAZINE THRUSTERS (RESISTOJETS)
(Commercial Communication Satellites)

The EURECA free-flying platform is illustrated in Figure 2 with its ion propulsion package (Giessen/MBB), the RIT-10 thruster, and a flight version of the power processor. The RIT-10, originally a mercury thruster, was converted to xenon and has been flight qualified. The Eureca is being readied for orbital test while awaiting resumption of shuttle launches.

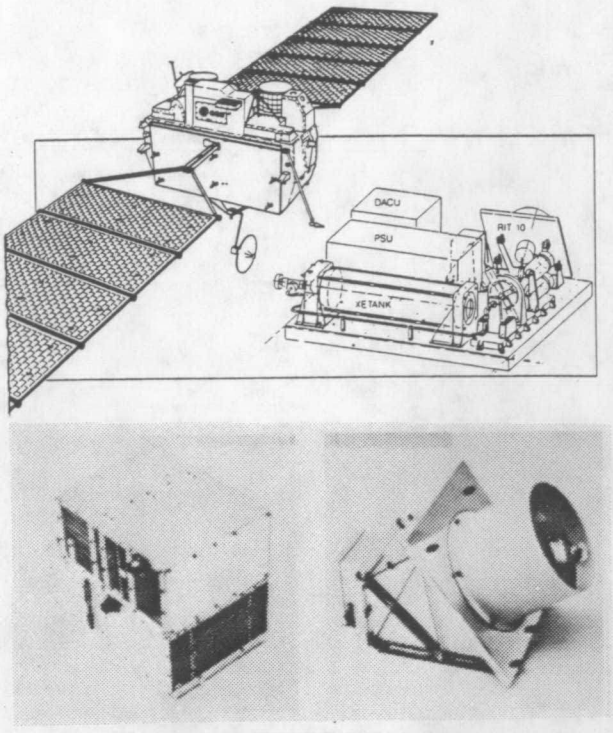

FIGURE 2
XENON ION FLIGHT HARDWARE (RIT-10)
(Eureca Space Platform)

Japan successfully flew an MPD arcjet system as a Spacelab-I experiment in 1983 and two small mercury ion engines on the Experimental Technology Satellite ETS-III during 1982 and 1983. They are seen atop the spacecraft in Figure 3. A larger four thruster xenon ion system (XIES) is currently being qualified for operational stationkeeping on the ETS-VI to be launched in 1992.

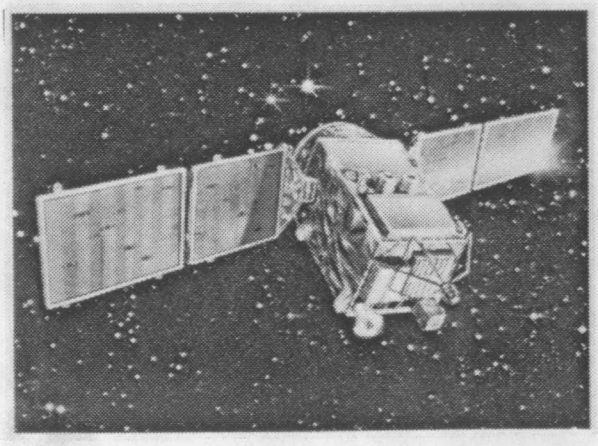

FIGURE 3
EXPERIMENTAL TEST SATELLITE, ETS-III (JAPAN)
(Ion Propulsion Station Keeping)

The XIES flight thruster is seen in Figure 4 with other xenon thruster designs sized for satellite stationkeeping and ready for flight application. The Hughes advanced development model (ADM) is a production model evolved from original development work funded by INTELSAT, while the UK-10 is currently in its advanced development stage. Many reports and papers provide details of these units, including brief summaries by the author.[1,2]

FIGURE 4
LOW POWER XENON ION THRUSTERS
(Satellite Stationkeeping)

The low thrust resistojet system for the space station that will use waste gases as propellant (Figure 5) has demonstrated life in excess of 6000 hours at NASA Lewis. An integrated flight type vaporizer/resistojet has also been developed for use with liquid water in the same application.

Possible EP application to electric stages for deploying navigation (ex: GPS) and SDIO satellites involves both arcjet and ion systems. The advantage of EP over chemical systems for this type of mission is illustrated by some comparative values in Figure 6, where chemical bipropellants (at I_s=440 sec) are compared to an ammonia arcjet system (at I_s=1050 sec) for the upper transfer stage. The basic assumption for the figure is the very rapid deployment (one launch per week) of 80 large surveillance platforms (35000 kg + 150 kWe of payload power) to a 2000 km polar orbit. Two launch vehicles are also compared; an advanced launch system, ALS (49,000 kg to 300 km at 70° inclination) and a heavy lift launch vehicle, HLLV

(99,000 kg to the ALS injection orbit). It is seen that the total number of launches, as well as the total deployment time, is significantly reduced with the arcjet system.

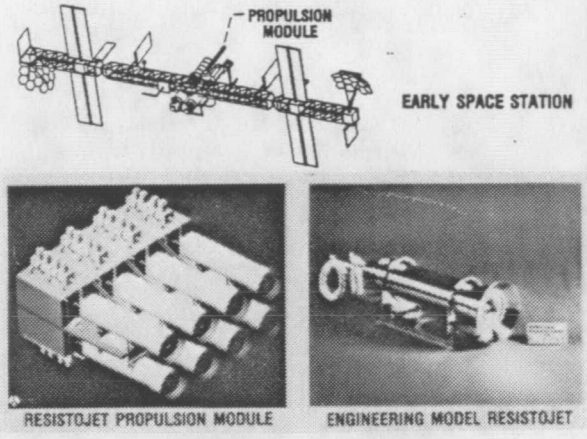

FIGURE 5
MULTIPROPELLANT RESISTOJETS
(Spacestation Drag Makeup)

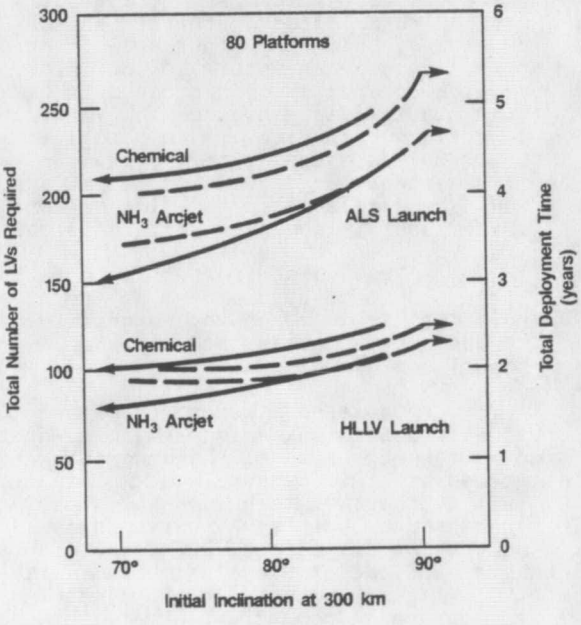

FIGURE 6
SPACE PLATFORM DEPLOYMENT

Work is also proceeding on high-powered ion thrusters at sizes and power levels well beyond that illustrated in Figure 7, where a pair of 5kWe xenon ion thrusters are seen operating with a single central neutralizer at JPL.

The current generation of communications satellites has more than sufficient solar and battery power for EP stationkeeping using electrothermal hydrazine, arcjets or ion thrusters.

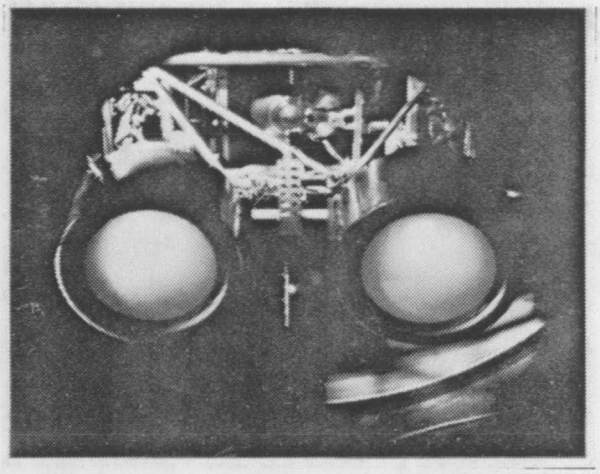

FIGURE 7
HIGH POWER ION THRUSTER TEST

Essentially the same power tehnology is also capable of fullfilling the needs of a number of transfer stage concepts. The survivable solar power (SUPER) and the SP-100 nuclear electric source are receiving sizable development support for this type of advanced mission. The SDIO SUPER array is being planned so as to have flight hardware in 1992 for a flight demonstration in 1993 with the electric propulsion "payload" currently undefined.

The lunar transfer reference mission of Table 3 as envisioned by JPL[3] is illustrated in Figure 8 where an electric stage using two banks of six high-power ion thrusters and its cargo are seen in lunar orbit.

FIGURE 8
ELECTRIC PROPULSION LUNAR TRANSFER

SDIO is pursuing all aspects of high-power (≈30kW) arcjets to perpare for flight demonstration with the SP-100 nuclear power source. In additon, a ground system test of the SP-100 to validate technical readiness is planned for 1992 with a flight in 1996 utilizing the

currently baselined arcjet payload. Fig. 9 shows the proposed spacecraft configuration for this Space Nuclear Power System (SNPS) Reference Mission.[4]

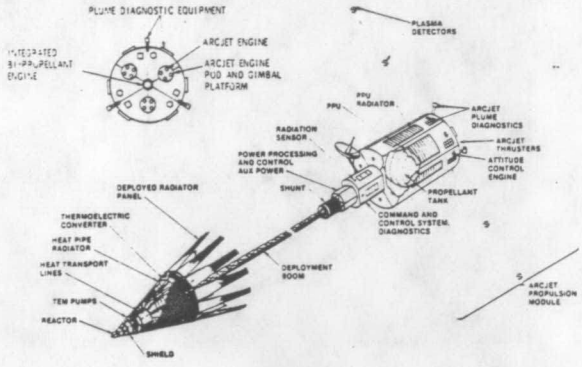

FIGURE 9
SPACE NUCLEAR POWER REFERENCE MISSION
(SP-100-Arcjet Propulsion Module)

One example of a spacecraft for solar system exploration is in Fig. 10 where an Electric Propulsion Module (EPM), utilizing 6, 200 mN RIT-35 ion thrusters (MBB), is seen on the reference design spacecraft AGORA.

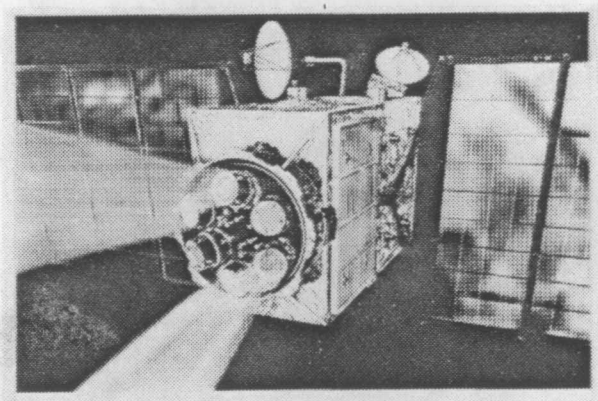

FIGURE 10
ELECTRIC PROPULSION MODULE
(Solar System Exploration)

Further downstream is the Mars mission where NASA scenario studies suggest the possibility of two vehicle types. One manned and capable of rapid transfer using advanced chemical propulsion. The other, an electrically propelled cargo vehicle would use either MPD or ion thrusters and carry large payloads. At the required megawatt power levels, large thrusters, nuclear power sources, and extensive test facilities will all require well-planned and adequately-funded development efforts. The USSR recently fixed 1994 as the beginning of their Mars program[5] and for a scenario using the new Energia heavy-lift booster and a totally new spacecraft, nuclear electric propulsion systems (NEJ) are indicated as sketched in Fig. 11.

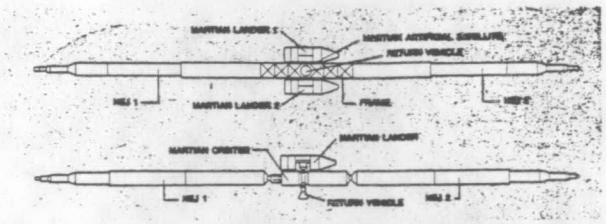

FIGURE 11
NUCLEAR ELECTRIC MARS MISSION CONCEPTS
(Sample Return & Manned Landing)

Thus, EP missions include commercial and scientific satellites, the near-term NASA space station, Air Force and SDIO orbit transfer and deployment, as well as mid-and far-term exploratory missions such as that to Mars.

IV. MISSION, ISSUES AND TECHNOLOGY

The nature of EP issues that need to be answered at any given time is first a function of mission maturity and applicable EP development status. Initial studies of possible mission options utilizing estimates of EP system performance and characteristics, evolve over a period of years into specific mission scenaria matched to selected spacecraft and EP technology. Ideally, the development of power sources, thrusters, electronics, and other EP elements would proceed in parallel with mission planning such that questions of utility, benefits and compatibility could be addressed as they arise, and mature power and propulsion technology would be available at the time of final system definition and mission go-ahead.

That this situation is not the case is evident by the general lag in space power development, uneven progress with EP technology, and unfocused mission priorities and direction.

The easy missions, such as satellite stationkeeping and space-station drag make-up, are well defined for spacecraft that currently have more than sufficient power resources and where operational benefits have been shown for EP at the low end of its performance range. This application is well in hand, with fully mature hydrazine resistojets in common use on commerical satellites and with advanced development waste gas resistojets baselined for the Space Station.

However, the benefits to GEO satellites that would accrue from the ten-fold performance increase offered the mature ion technology seen in Figure 4, are only now overcoming residual concerns based, for the most part, on cost and risk issues. Commercial satellite managers need to be convinced beyond doubt that there will be a sizable monetary return with little risk before venturing forth with advanced technologies.

The more difficult missions for the near term and future (Table 3) are less well defined. Their planners have the present problem of sorting out which power (solar/nuclear) and EP technologies (arcjet/ion/MPD) should be compared in trade offs with chemical systems and, further, which should be provided development support. Here, all the "Phase 3 Issues" of Table 2 are being pursued in various combinations and at various levels of detail.

High-power arcjets and ion thrusters, both under advanced development, have been suggested in Section III for constellation deployment, lunar transfer, and scientific exploration missions. In the power area, a number of developmental projects on large high-power solar arrays have been initiated, and work on kilowatt nuclear sources -- the SP-100 in the United States and a third-generation space reactor in Russia -- continue. MPD thrusters matched to megawatt power sources for propelling very large spacecraft await definition.

V. CONCLUSION

All of these advanced missions are large in scope and, except for the Space Station, involve high-power primary EP systems that require including equally sizable power sources. They are missions of national interest, involving systems of a size that require governmental direction, organization, and backing.

In parallel, the electric propulsion community has the opportunity to use the critical mass of studies, development effort, test experience, flight experiments, and evolved hardware amassed over the past 30 years in providing convincing answers to the "Phase 3 Issues."

We can also promote current mission studies that increasingly show EP as an economically enabling solution to advanced mission propulsion needs.

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