IN-SPACE PROPULSION—WHERE WE STAND AND WHAT'S NEXT

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ABSTRACT

The focus of this paper will be on the three stages of in-space transportation propulsion systems, now commonly referred to as in-space propulsion (ISP); i.e., the transfer of payloads from low-Earth orbits into higher orbits or into trajectories for planetary encounters, including planetary landers and sample return launchers, if required. Functions required at the operational location where ISP must provide thrust for orbit include maintenance, position control, stationkeeping, and spacecraft altitude control; i.e., proper pointing and dynamic stability in inertial space; and the third function set to enable operations at various planetary locations, such as atmospheric entry and capture, descent to the surface and ascent, back to rendezvous orbit. The discussion will concentrate on where ISP stands today and some observations of what might be next in line for new ISP technologies and systems for near-term and future flight applications. The architectural choices that are applicable for ISP will also be described and discussed in detail.

INTRODUCTION

After the payload is placed in a low-Earth parking orbit by the launcher, an upper stage is frequently used to transfer the payload to its operational orbit. Upper stage designs, especially their weight and size, are strongly driven by the performance and weight efficiency of their primary propulsion system. The specific impulse (I_{sp}), propellant density, and overall stage mass fraction of the primary propulsion system are key parameters. However, because of the lack of development of higher performance upper stages, especially those that would be compatible with reusable launch vehicles as well as expendable launch vehicles, many spacecraft suppliers, such as Boeing (formerly Hughes), Loral, and Northrop-Grumman (formerly TRW), have developed integral propulsion systems (IPSs) on board their spacecraft to perform many of the more conventional orbit transfer functions. Some examples include the Hughes 601 and 702 commercial series of satellite buses and the Northrop-Grumman IPS for the recent Chandra final orbit insertion functions. There have only been three complete upper stages developed over the last 30 years: (1) The basic Centaur and all the associated upgrades, (2) the advanced Centaurs for the Delta 3 and 4 and the Atlas 3 and 5, and (3) the inertial upper stage which is the only upper stage that is currently certified for launch in a shuttle. This has forced spacecraft/payload suppliers to develop advanced onboard IPSs to economically meet their needs, primarily with their own financial investments. Unfortunately, major dependence on in-house development funding has minimized the capability of IPSs as well as significantly increased their operational risk in many cases.

ASSESSMENT OF CURRENT STATUS

In-space Propulsion Functions

Table 1 lists the primary upper stage and spacecraft (in-space) propulsion options. Cold gas propulsion systems are inexpensive, low-performance systems that are rarely used unless there is an overriding requirement to avoid the hot gases and/or perceived safety concerns for liquid and solid systems. Solid propellant-based systems have been used extensively for orbital insertion, but the spacecraft's propulsion subsystem must be augmented with another technology to provide orbital maintenance maneuvering, velocity control,

Table 1. Principal options for spacecraft propulsion subsystems.

Propulsion Technology	Orbit Insertion		Orbit Maintenance and Maneuvering	Attitude Control	Typical Steady State I_{sp} (s)
	Perigee	Apogee			
Cold Gas			√	√	30–70
Solid	√	√			280–300
Liquid					
Monopropellant			√	√	220–240
Bipropellant	√	√	√	√	305–310
Dual Mode	√	√	√	√	313–322
Hybrid	√	√	√		250–340
Electric		√	√		300–10,000
Electrothermal		√	√	√	300–700
Electrostatic		√	√	√	2,000–10,000
Electromagnetic		√	√		3,000–6,000

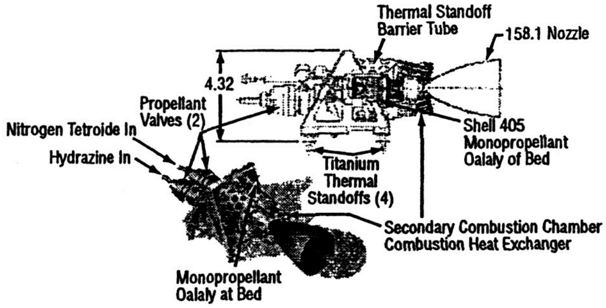

Figure 1. Secondary combustion augmented thruster—bimodal spacecraft attitude and velocity control RCS thruster.

and attitude control. Liquid systems are divided into monopropellant and bipropellant systems with a third alternative, dual mode; i.e., a bipropellant derivative. Monopropellant systems have successfully provided orbital maintenance control and attitude control functions for hundreds of spacecraft but lack the performance to provide high-efficiency, large ΔV maneuvers required for orbital insertion. Bipropellant systems are attractive because they can provide all three functions with one higher performance system, but they are more complex than the historic solid rocket and monopropellant combined systems.

Dual-mode systems are integrated monopropellant and bipropellant systems fed by common fuel tanks. These systems are actually hybrid designs that use hydrazine (N_2H_4) as a fuel for high-performance bipropellant engines; i.e., nitrogen tetroxide/hydrazine (N_2O_4/N_2H_4), and as a monopropellant with conventional low-thrust catalytic thrusters. The N_2O_4 feeds into the bipropellant engines and the monopropellant thrusters from a common fuel tank. In this manner, they can provide high I_{sp} for long ΔV burns at high thrust from a single propulsion system; e.g., apogee circularization, and reliable, precise, minimum-impulse burns by the monopropellant thrusters for attitude control and tight pointing. An additional capability to enhance dual-mode propulsion is the development of a bimodal-thrust device, which can operate in a bimodal manner, either as a simple catalytic-monopropellant thruster or as a high-performance, bipropellant thruster, known as the secondary combustion augmented thruster (SCAT) shown in Figure 1.

In the propulsion system selection process, practical consideration may restrict the propellant choices to those that are readily available, storable, and easy to handle. Also, we must weigh the lead time needed to develop new hardware against any limitations from using a combination of existing components or stages. Finally, limits on payload acceleration may dictate the maximum permissible thrust levels.

Liquid Rockets for Upper Stage and Spacecraft Propulsion Systems

In a liquid rocket system, propellants are stored as liquids in tanks and fed on demand into the combustion chamber by gas pressurization or a pump. Bipropellant engines chemically react a fuel and an oxidizer, and monopropellant engines catalytically decompose a single propellant. Bipropellant engines deliver a higher I_{sp} but involve additional system complexity and cost. Table 2 shows liquid rocket engines currently in use for upper stages or IPSs on spacecraft. For up-to-date and more detailed information, contact the respective developers.

Electric Propulsion

Electric propulsion (EP) uses externally provided electrical power, either from the Sun (converted through photovoltaic solar arrays—100% to date) or from nuclear and thermodynamic conversion thermal engines (to accelerate the working fluid to produce useful thrust). For example, in an ion engine, an electric field accelerates charged particles that exit at high velocity. Alternatively, in a magnetoplasmadynamic thruster, a current-carrying plasma interacts with a magnetic field, resulting in a Lorentz acceleration to expel the plasma.

Table 2. Examples of available liquid rocket engines.

Engine	Developer	Nominal Thrust (N)	I_{sp} (s)	Propellants	Oper. Life (s)	Engine Mass (kg)	Status
XLR-132	Rocketdyne	1.67×10^4	340	N_2O_4/MMH	5,000	51.26	In development
Transtar	Aerojet	1.67×10^4	330–338	N_2O_4/MMH	5,400	57.15	In development
Transtage	Aerojet	3.56×10^4	315	N_2O_4/A-50	1,000	107.95	Flown
Delta-II	Aerojet	4.36×10^4	320	N_2O_4/MMH	1,200	99.79	Flown
R-4D	Marquardt	4.00×10^3	309	N_2O_4/MMH	25,000	7.26	Qualified
OME/UR	Aerojet	2.67×10^4	340	N_2O_4/MMH	1,200	90.72	Modified orbiter maneuvering engine
RL10-A	Pratt & Whitney	7.34×10^4	446	LO_2/LH_2	400	138.35	Flight qualified (Centaur)
DM/LAE	TRW	4.45×10^2	315	N_2O_4/N_4H_4	15,000	4.54	Flown
R4-D	Marquardt	4.89×10^2	310	N_2O_4/MMH	20,000	3.76	Flown
R42	Marquardt	8.90×10^2	305	MON-3/MMH	15,000	4.54	Qualified
MMBPS	TRW	4.45×10^2	302	N_2O_4/MMH	20,000	5.22	Flight qualified
RS-41	Rocketdyne	1.11×10^4	312	N_2O_4/MMH	2,000	113.40	Flight qualified (Peacekeeper)
ADLAE	TRW	4.45×10^2	330	N_2O_4/N_2H_4	28,000	4.50	In qual.
Chandra X-Ray Observatory	TRW	4.25×10^3	322.5	N_2O_4/N_2H_4	25,000	4.50	Flight qualified
HS 601 AKE	ARC/LPG	4.89×10^2	312	N_2O_4/MMH	10,000	4.08	In development
R-40A	Marquardt	4.00×10^3	309	N_2O_4/MMH	25,000	7.26	Qualified(mod. of Shuttle RCS engine)
HPLAM	TRW	4.45×10^2	325	N_2O_4/MMH	30,000	4.60	In advanced development

No fundamental limit is known for the exhaust velocity that can be obtained with an electric rocket other than the speed of light. However, the power required may grow to the point where further acceleration is pointless. Therefore, there is an optimum exhaust velocity, and hence an optimum I_{sp} that largely depends on the electric power subsystem.[1]

Spacecraft Electric Propulsion Systems Design Concepts

The five EP concepts shown in Table 3 have achieved operational status, and many programs are underway to increase the number and types of missions served by EP. The following paragraphs briefly highlight the characteristics of mature EP systems that have become operational, or for which near-term flight programs are firmly planned, and comment on the potentials of various classes of EP systems. Table 4 illustrates the three basic types of electrical energy thrusters. Table 3 and Figure 2 show key characteristics of selected, mature EP systems. Figure 2 illustrates the fundamental concepts that enable operations for all EP systems. To mitigate the effects of mission specifics, the system specific mass (lbm/kW (kg/kW)) only includes the mass of the

Table 3. Characteristics of selected electric propulsion flight systems.

Concept	Characteristics					
	I_{sp} (s)	Input Power (kW)	Thrust/ Power (mN/kW)	Specific Mass (kg/kW)	Propellant	Supplier
Resistojet	296	0.5	743	1.6	N_2H_4	Aerojet
	299	0.9	905	1.0	N_2H_4	Aerojet, TRW
Arc jet	480	0.85	135	3.5	NH_3	IRS/ITT
	502	1.8	138	3.1	N_2H_4	Aerojet
	>580	2.17	113	2.5	N_2H_4	Aerojet
	800	26*	–	–	NH_3	TRW, Aerojet, CTA
Pulsed plasma thruster	847	<0.03†	20.8	195.0	Teflon	JHU/APL
	1,200	<0.02†	16.1	85.0	Teflon	Aerojet, TsNIIMASH, NASA
Hall effect thruster	1,600	1.5	55	7.0	Xenon	IST, Loral, Fakel
	1,638	1.4*	–	–	Xenon	TsNIIMASH, NASA
	2,042	4.5	54.3	6.0	Xenon	SPI, KeRC
Ion thruster	2,585	0.5	35.6	23.6	Xenon	HAC
	2,905	0.74	37.3	22.0	Xenon	MELCO, Toshiba
	3,250	0.6	30	25.0	Xenon	MMS
	3,280	2.5	41	9.1	Xenon	HAC, NASA
	3,400	0.6	25.6	23.7	Xenon	DASA

*Thruster input power
†Power dependent on pulse rate

Table 4. Electric propulsion—three classes of accelerator concepts.

Electrothermal	Electrostatic	Electromagnetic
• Gas heated via resistance element or arc and expanded through nozzle • Resistojets • Arc jets	• Ions electrostatically accelerated • Hall effect • Ion • Field emission	• Plasma accelerated via interaction of current and magnetic field • Pulsed plasma • Magnetoplasmadynamic • Pulsed inductive
Power Range 0.4–2 kW	1–50 kW	50 kW–1 MW
I_{sp} 300–800 s	1,000–3,000 s	2,000–5,000 s

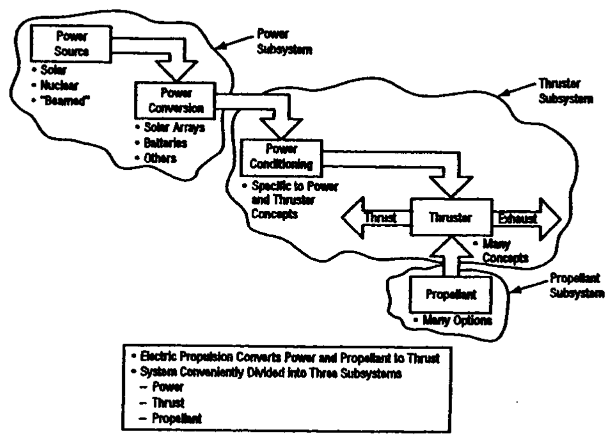

Figure 2. Functional block diagram of generic electric propulsion system

thruster and power processor. (The masses of the propellant subsystem, gimbals, and other mission specifics are not included.)

Resistojets have been used for North-South stationkeeping and orbital insertion of communication satellites in the United States (U.S.) and for orbital control and attitude control system (ACS) functions on Russian spacecraft, respectively. Propellant temperatures are fundamentally determined by material limits in resistojets, which implies modest (propellant-specific) maxima for I_{sp} of ≈300 s for the 0.5- to 1-kW class resistojets.

Resistojets have several desirable features, including (1) values of thrust and power far higher than other EP options, due to their high efficiencies and modest I_{sp}; (2) the lowest EP system dry masses, primarily due to the lack of a requirement for a power processor; and (3) uncharged (benign) plumes. These features will continue to make resistojets attractive for low to modest energy applications, especially where power limits, thrusting times, and plume impacts are mission drivers. In addition, resistojets can operate on a wide variety of propellants, which leads to their proposed use as a propulsion and waste gas management concept on the *International Space Station* (*ISS*) and as an Earth-orbit insertion system (operated on hydrogen).

Arc jets provide about twice the I_{sp} of resistojets while still maintaining some desirable electrothermal features, such as use of standard propellants and relatively low dry masses. The increased I_{sp} coupled with relatively low efficiencies of about 0.3 to 0.4 leads to significant decreases (>6 times) of thrust and power relative to resistojets. In addition, because we must control the complex plasma and arc phenomena, arc jets require relatively complex power conditioning, resulting in dry masses about twice those of resistojet systems.

Significant efforts, including development of novel materials, were necessary to define and validate the 600-s N_2H_4 arc jet. It is expected, therefore, that 600–650 s represents the upper range of I_{sp} that can be expected from low-power arc jets using storable propellants. Arc jets do provide major mass benefits for many spacecraft, are relatively simple to integrate, and are the least complex and costly of any plasma propulsion device. For these reasons, it is also expected that low-power arc jets will undergo evolutionary improvements and be used well into the future for a variety of medium to high energy propulsion functions.

Pulsed plasma thrusters (PPTs) are inherently pulsed devices that operate at ≈847-s I_{sp}. They were built in the Applied Physics Laboratory at Johns Hopkins University and have successfully maintained precision control of three NOVA spacecraft for many years. PPTs feature very small ($\leq 4\times10^{-4}$ N·s) impulse bit capability, use of a solid propellant (Teflon® by DuPont®), and the ability to operate at near constant performance over large power ranges. An improved version PPT that operates at ≈1,200-s I_{sp} (Table 3) was developed under NASA leadership, and a flight test was recently conducted on the Earth Observer 1 spacecraft that very successfully demonstrated propulsive ACS. The characteristics of PPTs will likely limit their power operating range to under a few hundred watts and, as suggested by Table 5, they have large specific masses. Within their operating capability, however, PPTs promise a combination of low power, high I_{sp}, and a small impulse bit that is unique. Based on recent successes on flight vehicles, it is expected that PPTs' use for ACSs and for modest energy ΔV applications in small spacecraft where the power and thrust limitations of PPTs are acceptable and desirable.

Hall effect thrusters (HETs) and ion thrusters (ITs) represent the highest performance EP options; characteristics of mature versions of both concepts are shown in Table 5. HETs were developed and flown on dozens of Russian space missions for various functions and are under intense development for use on other nations' spacecraft. Flight-type HETs have been produced by Fakel Enterprise (Fakel), Keldysh Research Center (KeRC), and TsNIIMASH, all of Russia, and quite aggressive HET research and development programs are in place in Europe, Japan, and the United States. Table 5 lists three HET concepts to illustrate the state of the art. The 1,600-s I_{sp} concept was developed to flight-ready status by a team, including International Space Technology, Inc., Loral, and Fakel. The 1,638-s I_{sp} device was built, qualified, and delivered for flight test (at reduced levels of power and I_{sp}) by a NASA/industry team. The high-power HET was built by Space Power Inc. and KeRC for a 1999 flight test on a Russian GEOSAT. In addition, two versions of 1.5-kW class HETs traceable to the Fakel concept are planned to provide stationkeeping on

Table 5. Hall effect thruster status summary.

Concept	Supplier	Power (kW)	I_{sp}	T (mN)	Dome Life (Khr)	Maturity	Comment
SPT–100	Fakel (Russia)	1.35	1,500	83	>5.7	Flight	Most mature 1.5-kW class concept. Multiple life tests >5 Khr
D–55	TsNIIMASH (Russia)	1.39	1,638	88.6	0.64	Under development	Several technical differences from SPT–100
T–100	KeRC (Russia)	1.29	1,650	80	0.63	Under development	Nearly identical to SPT–100
SPT–140	Fakel (Russia)	3.0 5.0	1,579 1,929	177 263	–	Under development	Operated from 1.5 to 5 kW
D–100	TsNIIMASH	3.0	1,849	184	–	Under development	–
T–160E, T–140, T–200	KeRC SPI (USA)	3.0 4.3	1,772 1,909	192 257	– –	Under development	New high-fidelity data from NASA

the French Stentor spacecraft for 9 years. Table 5 summarizes the status of HETs.

Five mature ion thrusters are also shown in Table 3. The 2,585-s I_{sp} system was built by the Boeing Space Systems and is operational on a commercial communication satellite (COMSAT) that was launched in 1997. The 2,906-s I_{sp} concept was built by a team from Mitsubishi Electric Corporation and Toshiba Corporation, Japan, and was flown on the ETS–VI spacecraft in 1994. An orbital insertion issue prevented the system from performing its planned stationkeeping function, but in-space characterizations were performed in 1995 and an identical system was flown on the Japanese COMETS spacecraft. The 3,250-s and 3,400-s I_{sp} systems were built in Europe by teams headed by Matra Marconi Space and DASA, respectively. These devices were baselined for stationkeeping on the European Space Agency's Artemis spacecraft that was launched in July 2001. The 3,280-s, 2.5-kW device is the highest power mature IT for which data are available and was very successfully demonstrated on NASA's New Millennium DS–1 mission.

HETs and ITs are the highest I_{sp} options available for mission planners; many analyses have been conducted to evaluate their use for high-energy missions. Comparison of the two devices is difficult because of the relative lack of maturity of devices built to comparable power levels and standards. ITs operate more reliably at higher I_{sp} than HETs, and their performance and specific mass are deeply penalized by operation at I_{sp} less than ≈2,500 s because of the constraints imposed by the ion optics systems. On the other hand, HET systems have 30% or greater thrust and power levels than those of ITs and are considerably lighter, but HET operations above ≈2,500-s pose major lifetime or redesign challenges. Both concepts eject high-velocity, charged plumes and present approximately the same issues regarding spacecraft integration. HETs and ITs provide extreme benefits for emerging space missions and the choice between them will be very mission specific. In general, however, ITs become increasingly beneficial as mission energies increase, and HETs appear optimum for many time-constrained situations typical of Earth-orbiting space missions.

Electric propulsion has come a long way in the last decade. For example, as mentioned above, the development and highly successful flight demonstration of a long-life, high-performance ion EP system, known as NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) (part of the flight demonstration project known as Deep Space 1), was part of the discovery series of missions. This effort was mainly funded by NASA, although private investment was also provided by the contractor who now uses a derivative xenon ion propulsion system (XIPS) for their family of commercial COMSATs.

This ion propulsion system demonstration for deep space exploration missions (the NSTAR program) was conducted jointly by Glenn Research Center and the Jet Propulsion Laboratory with industry participation.[2] Flown on the Deep Space 1 spacecraft under the new millennium program, launch in 1998, NSTAR was the first interplanetary spacecraft to use ion thrusters as main propulsion. The NSTAR engine uses xenon propellant, has a 30-cm optics diameter, and was operated at 0.5–2 kW in flight. The engine was designed for 8,000 hours life and has performed well in flight, already exceeding 25,000 hours of reliable operation in space. Also noteworthy is that commercial COMSATs now routinely utilize ion propulsion for stationkeeping; the first of these was launched in 1997.

In chemical propulsion for upper stages and onboard IPSs, only minimal investment has been provided by the U.S. Government. The paucity of new technology developments for the high leverage of increased performance ISP systems has greatly hampered the growth of Earth orbital and deep space missions. Many of these new high-performance ISP technologies are literally required to enable future planned space exploration missions. This need was recognized by the NASA office of space science, who then initiated a comprehensive series of procurement programs to develop these badly needed, high-leverage, propulsion development programs. For typical classes of spacecraft using today's conventional ISP, as shown in Figure 3, it can be seen that 30% to 60% of all the mass launched into low-Earth parking orbit is for injection and maneuvering propellant. However, in the case of a large, deep space probe spacecraft, such as the Cassini (soon to be placed into a Saturn orbit), launched by a Titan IV Centaur, almost all of the launched mass is spacecraft and upper stage propellant (≈95%, which allows little capability for spacecraft power, avionics, structure, and the scientific instrument payload), as shown in Figure 4.

Propulsion components will also be critical to the success of future in-space transportation systems. The development of advanced, robust, lightweight components, such as valves, tanks, and

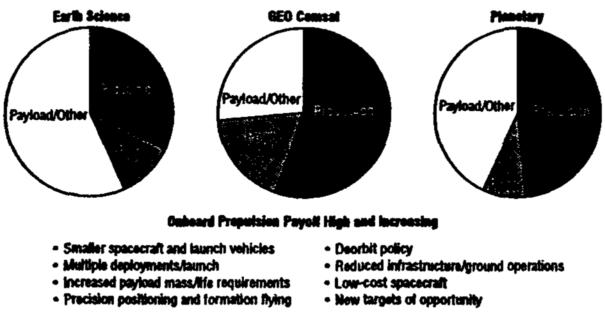

Figure 3. Typical spacecraft mass fractions—over half of everything launched is on-board propulsion.

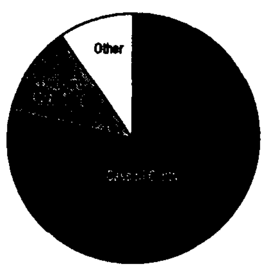

Figure 4. In -space propulsion requirements: deep-space robotic example—Cassini.

regulation devices, that will enable appropriate systems with high performance that offer improved high reliability for future deep space missions is also critical for enhancing future missions.

Above all, very low-density, high-temperature capable, high-strength actively and passively cooled materials with their associated structural architecture will be critical. It is projected that toward the end of the next decade, ceramic-based systems will find their way into more critical components and applications and will likely be one of the breakthroughs that can be touted in a similar paper written 10 years from now. Advanced metallics with properties substantially improved over those of today's operational materials will be employed extensively. Another possibility for certain types of structures will be higher temperature, polymer-based materials.

By the end of the next decade, another revolution in design tool and design capability will probably have taken place. A broader and deeper understanding of physics is gained through advanced sensing techniques, coupled with improved numerical and simulation methods; and further, with health management gains through better experimentation and technology demonstration should greatly increase the quantity of design options that can be addressed, the number of iterations that can be rapidly and accurately accomplished, the level of detail and fidelity in the analysis, and reductions in uncertainty and product design and development cycle times.

In summary, by the end of this decade, the capabilities and tools should be well in hand that will allow major advancements toward the first integrated systems that incorporate all the key technologies and demonstrate end-to-end mission, operational, safety, and economic performance potential.

Recent Advancements

Technology advancements for in-space transportation have occurred in three primary categories: advanced materials, engine designs and propellants for chemical propulsion, and development and demonstration of EP and soon-to-be-flown propellantless systems. These advancements are summarized in Figure 5.

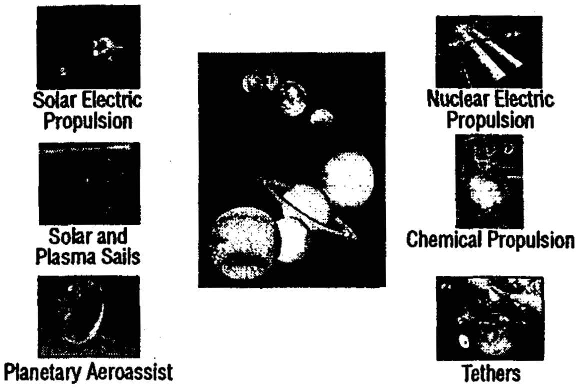

Figure 5. In-space propulsion systems.

In chemical propulsion, development of iridium-rhenium chambers pioneered by NASA and industry started in the 1980's. During the 1990's, this technology was brought from a low technology readiness level of maturity to full operational use. This provided substantial advancement in performance parameters for monopropellant and bipropellant systems, offering long life at increased I_{sp} (323 s in qualification testing).[3] The first flight occurred in 1999. In addition, major advancements in spacecraft dual-mode propulsion systems; i.e., using N_2H_4 as both a bipropellant fuel and as a monopropellant fuel in the same system, have enabled higher spacecraft performance and operational benefits, such as was the case for the Chandra x-ray telescope.

Although not yet implemented in a flight program, substantial progress has been made in hydroxyl azide nitride (HAN)-based, monopropellant spacecraft propulsion thrusters which have acceptable I_{sp} and good density-impulse characteristics. This is important because increasingly strict safety and environmental regulations as well as operations costs make it steadily more difficult to utilize traditional monopropellants. During the 1990's, stable HAN-based monopropellant mixes with laboratory thrusters using catalytic ignition were demonstrated with over 8,000 s of cumulative operation on a single catalyst/thruster combination. The result was accomplished by an industry/Glenn Research Center team. The results will likely open the door to further development and eventual adoption for spacecraft use.

Electric

Substantial gains occurred in EP during the 1990's. Electric propulsion has very low thrust but extremely high I_{sp}. Appropriate use through mission design and availability of adequate spacecraft power, coupled with advancements made in thruster technology, has brought widespread application within reach due to the substantial competitive advantage, cost reduction, or mission-enabling advantages provided. Often, EP can mean the difference in launch vehicle class, substantial addition to payload mass, or feasibility of a deep space exploration mission.

Another significant advancement in EP was achieved through development of the plasma contactor for the *ISS*. This device is essentially the same as a hollow cathode required for neutralization in an electrostatic propulsion system. The *ISS* hollow cathode assembly—designed, developed, built, and tested at Glenn Research Center—accumulated 27,800 hours of operation during life test, demonstrating very long life for an essential propulsion system component.

Propellantless

Advancements have also been made in the so-called propellantless categories that include solar sail and tethers, shown in Figure 6. A series of systems tests on propellant-free propulsion technology have recently been completed at the NASA Marshall Space Flight Center (MSFC) in Huntsville. The Propulsive Small Expendable Deployer System (ProSEDS) is a tether-based propulsion system that draws power from the space environment around Earth, allowing the transfer of energy from the Earth to the spacecraft. Electrodynamic tethers used for the propulsion in low-Earth orbit and beyond could significantly reduce the weight of upper stage rockets used to boost spacecraft to higher orbit. And because they require no propellant, electrodynamic tethers substantially reduce spacecraft weight, providing a cheap, efficient method of reboosting the orbits of spacecraft and potentially the *ISS*.

An electrodynamic tether, which consists of a long, thin wire deployed from an orbiting satellite or vehicle, uses the same principles as electric motors in many household appliances and automobile

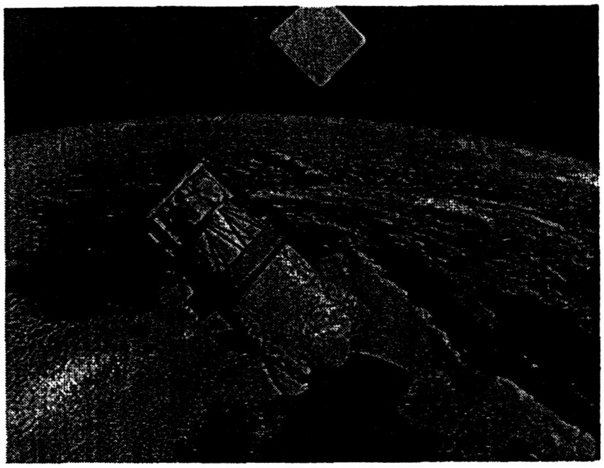

Figure 6. Tether being used to maneuver a satellite in space.

generators. When a wire moves through a magnetic field, an electrical current results. As this current flows through the wire, it experiences a push from any external magnetic field. The force exerted on the tether by the magnetic field can be used to raise or lower a satellite's orbit, depending on the direction of the current's flow.

Researchers at MSFC also are investigating the use of electrodynamic tethers to extend and enhance future scientific missions to Jupiter and its moons. In theory, electrodynamic tether propulsion could be used near any planet with a significant magnetosphere, such as the enormous magnetosphere found around Jupiter.

As mentioned earlier, another category of propellantless propulsion is the solar sail. Solar sails use photon pressure of force on thin, lightweight reflective sheets to produce thrust. The net force or thrust on the solar sail is perpendicular to the surface, which is the result of a force tangential to orbit and a force perpendicular to the orbit caused by the reflective sunlight, as shown in Figure 7. Ideal reflection of sunlight from the solar sail surface produces 9 N/km^2 at 1 AU.

The Next Decade

Chemical propulsion offers a unique combination of features that for some mission requirements have no substitutes. It is likely that green (i.e., nontoxic) propellants will continue to be under technology development and begin to be introduced into

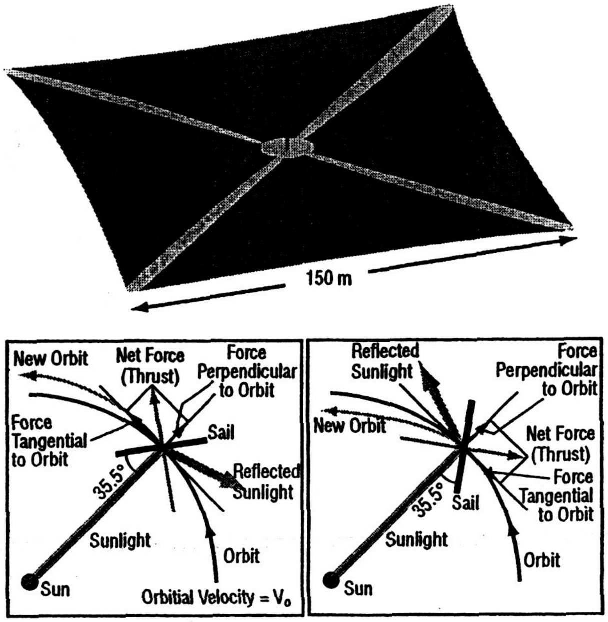

Figure 7. Solar sail and illustration of how thrust is derived from the reflection of the sunlight on the solar sail.

at least some operational missions. Planetary exploration will likely demand the extension of existing technologies to meet the unique needs of planetary transportation from surface to orbit.

Power output for spacecraft will continue to increase, affording the opportunity to substitute EP for chemical propulsion for main orbit transfer with acceptable transit times. Taking advantage of the higher power capability in a most advantageous fashion will demand increasing power capability from the thrusters with high efficiency. In both HET and IT systems, 10-kW maximum power thrusters are under technology development. Planetary exploration as well as multipurpose Earth orbit thrusting requires a wide operating range at acceptable efficiency. In the case of IT systems utilizing solar power for planetary exploration, the power available is steadily reduced as the distance from the Sun increases, placing important operational demands on the designs.

Another emerging trend is the availability of advanced power sources that lead to the capability of performing ambitious missions that need to optimize at high power, very high I_{sp} conditions. Thrusters to meet such demand will likely be demonstrated with a substantial level of maturity that might provide a point of departure for flight demonstration in the second decade of the century. A major advancement will be enabled by the development and implementation of very high-power (hundreds of kW_e to megawatts) nuclear electric propulsion (NEP) systems.

Exploration of the outer planets in our solar system represents significant technological challenges in mission planning and vehicle design. Long-duration missions currently utilize an optimized combination of chemical propellant, solar energy, and vehicle trajectories that require gravitational assistance. Using this conventional approach results in launch window time constraints, longer trip times, and limited power reserves for payload science.

To mitigate these mission constraints, NASA's nuclear power Prometheus program will focus on two types of nuclear power technology: (1) Nuclear fission electric propulsion and power systems and (2) radioisotope power systems. NEP will utilize a fission reactor, thermodynamic power conversion system, and electric thrusters to provide propulsion for a new class of exploration spacecraft. The NEP system will generate high I_{sp} (2,000–9,000 s) that will reduce the amount of propellant required for long-duration missions.

The development of the NEP spacecraft will eliminate the need to depend on complex trajectories with the usual gravity-assist constraints. The success of the Nuclear Propulsion and Power program will enable NASA to meet the higher power demand that will be required for exploration of the outer solar system. Through the utilization of nuclear technology, spacecraft will be able to operate over a period of years and cover vast distances previously impossible to accomplish with traditional fuel technology. Without the double constraints of mass and power to encumber those vehicles, spacecraft utilizing nuclear propulsion will be able to maneuver robustly and with flexibility, once on-Station, and will also be able to provide vastly improved data acquisition and transmission capability.

NASA's NEP protoflight spacecraft will be developed as part of the Prometheus program. This project will focus on the development of a fission-powered spacecraft, illustrated conceptually in Figure 8, that will tour and orbit three of Jupiter's moons—Europa, Ganymede, and Callisto. Science data from this mission will provide full orbital characterization of all three icy moons.

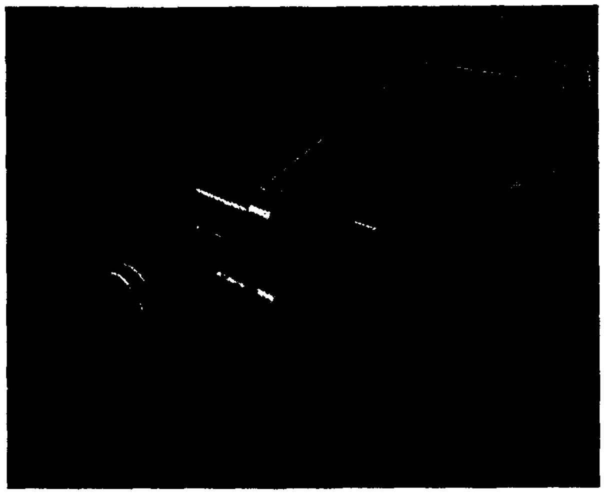

Figure 8. Conception of fission-powered space craft.

The Jupiter moons are believed to contain water beneath their icy crusts. There is spectral evidence that indicates salts and organic materials on their surfaces, and geological evidence indicates that an ocean existed on Europa within the last 100 million years. The Decadal Survey Report from the National Academy of Sciences identified the Europa mission as the top priority for solar system exploration.

Planetary surface exploration will be advanced by the development of a new generation of RPSs. The RPS generates electricity from heat created by the natural decay of plutonium. This advanced RPS will provide reliable power for surface mobility units, such as the Mars Smart Lander. Solar panels nominally provide the lander with 180 days of useful life; the advanced RPS would extend its lifetime to over 1,000 days. The RPS would relieve the lander of its dependency on solar power during the vehicle's greatly increased life on the planet's surface, thus enabling a broader exploration of the planet's surface.

Multiple agencies will be involved in the NSP program that will be funded through a combination of direct funding and competitive sourcing. These participants include NASA and the Department of Energy. NASA Field Centers involved include Marshall Space Flight Center, Glenn Research Center, and the Jet Propulsion Laboratory.

Near-term NSP goals will focus on the development of advanced RPSs, specifically the multimission radioisotope thermoelectric generator and the Stirling radioisotope generator, and identification of candidate planetary science missions enabled by NEP.

In the past decade, achievements in ISP saw the advent of EP technologies that were steadily developed for 30 years. These provide revolutionary performance improvements as well as necessitating changes in the way missions are performed to take advantage of the characteristics of the electric systems. Chemical propulsion also was improved in important ways. Technology development efforts begun in the 1990's became the basis for the propulsion advancements that are coming to fruition in this decade.

NASA's Integrated Space Transportation Architecture Plan provides the basis for a very challenging, creative, and productive next decade. The opportunity for a series of great strides in space transportation is upon us. NASA now has an administrator who strongly supports what we have identified and have planned to do. Although we have just come through some difficult, lean times and industry is still in a downturn, the future appears full of bright possibilities, which would not have been available without the many achievements of the 1990's.

NASA, along with its many worldwide partners, has been at the forefront of many of the most important ISP developments. This paper did not attempt to rigorously sort through all major advancements and assign perceived impacts to select those to be highlighted. Instead, it highlighted those that were noteworthy for the impacts they have on the direction NASA has planned to take in the future of space exploration.

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