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Selection and Prioritization of Advanced Propulsion Technologies for Future Space Missions

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Abstract

The exploration of our solar system will require spacecraft with much greater capability than spacecraft which have been launched in the past. This is particularly true for exploration of the outer planets. Outer planet exploration requires shorter trip times, increased payload mass, and ability to orbit or land on outer planets. Increased capability requires better propulsion systems, including increased specific impulse. Chemical propulsion systems are not capable of delivering the performance required for exploration of the solar system. Future propulsion systems will be applied to a wide variety of missions with a diverse set of mission requirements. Many candidate propulsion technologies have been proposed, but NASA resources do not permit development of all of them. Therefore, we need to rationally select a few propulsion technologies for advancement, for application to future space missions. An effort was initiated to select and prioritize candidate propulsion technologies for development investment. The results of the study identified Aerocapture, 5 - 10 kW Solar Electric Ion, and Nuclear Electric Propulsion as high priority technologies. Solar Sails, 100 Kw Solar Electric Hall Thrusters, Electric Propulsion, and Advanced Chemical were identified as medium priority technologies. Plasma sails, momentum exchange tethers, and low density solar sails were identified as high risk/high payoff technologies.

Introduction

Advanced In-Space Propulsion (ISP) technologies will enable much more effective exploration of our solar system and will permit mission designers to plan missions to "fly anytime, anywhere and complete a host of science objectives at the destinations" with greater reliability and safety. When compared with state-of-the-art chemical propulsion, increased capabilities include shorter trip times to outer planets, higher payload mass, and enabling of missions which are very difficult or impossible with chemical propulsion. Examples of these missions are orbits around the outer planets, interstellar probes, and sample return missions from Mars or other planets. With a wide range of possible missions and many candidate propulsion technologies with very diverse characteristics, the question of which technologies are "best" for future missions is a difficult one. Resource limitations do not permit the development of all candidate propulsion technologies. Therefore, it is required to develop a set of propulsion technologies which will adequately satisfy a broad spectrum of mission requirements.

The primary focus of IISTP efforts was: (1) develop, iterate and baseline future NASA requirements for In-Space Transportation; (2) define preliminary integrated architectures utilizing advanced ISP technologies; and (3) identify and prioritize ISP technologies.

The primary efforts of the IISTP efforts were to: (1) address missions, mission priorities, and mission requirements as defined by the various NASA enterprises; (2) provide a forum for technologists to advocate any ISP technology for any mission(s) for which they deemed their propulsion technology to be appropriate; (3) perform system analyses of the prioritized mission set to the degree necessary to support evaluation and prioritization of each technology advocated by the technologists; (4) perform cost analyses on each of the technologies that were determined by systems analyses to be viable candidates for the mission set; and (5) integrate all customer, technologist, systems, cost, and program inputs into the final IISTP prioritized set of technologies.

The primary products of the IISTP effort were: (1) prioritized set of advanced ISP technologies that meet customer-provided requirements for the customer prioritized mission set and (2) recommendations of relative technology payoffs to guide future NASA investment decisions.

This effort involved many people at most NASA centers. The effort was divided among several teams:

Table 1. Future NASA Missions as High Priority Candidates for Advanced Propulsion Technologies

Mission Category	Missions of Interest
Earth vicinity, low to moderate delta velocity (ΔV)	Geospace Electrodynamic Connection (GEC)
	Low Earth Orbit Synthetic Aperture Radar (LEO SAR)
	Natural Haz. & Soil Moisture Measurement SAR
	Earth Radiative Energy Meas. Facility (Leonardo)
	Magnetospheric Constellation (MC)
	Ionospheric Mappers
Inner solar system, simple profile, moderate ΔV	Space Interferometry Mission (SIM)
	StarLight ST-3
Inner solar system, sample return	Comet Nucleus Sample Return (CNSR)
	Mars Sample Return (MSR)
Inner solar system, complex profile, moderate to high ΔV	Earth Atmospheric Solar Occultation Imager (EASI)
	Pole-Sitter (PS)
	Sub L1 point mission
	Solar Sentinels
	Solar Polar Imager (SPI)
	Next Generation Space Telescope (NGST)
	Terrestrial Planet Finder (TPF)
	Outer Zodiacal Transfer
Outer solar system, simple profile, high ΔV	Outer Zodiacal Transfer
Outer solar system, complex profile	*Titan Explorer (TE) (Titan Organics Orbiter/Lander)*
	Neptune Orbiter (NO)
	Europa Lander (EL)
	Solar Probe
Beyond outer solar system	*Interstellar Probe (ISP)*
HEDS lunar, cislunar, and Earth vicinity	Moon and Earth-Moon libration points
	Sun-Earth libration points
HEDS asteroids / Mars vicinity	Near-Earth asteroids
	Mars Piloted (MP) and cargo

increase its ability to take seismic measurements. The planned 10 days of surface/subsurface analysis should provide valuable insight into the ice sheets and topography of this moon. The propulsion functions are similar to those for the Titan Explorer. Propulsion required for the descent to the surface was beyond the scope of this study.

Mars Sample Collection and Return

The Mars Sample Return mission is part of NASA's continued exploration of the red planet. The spacecraft will fly to Mars, land, and return with soil, rock, and atmospheric samples. Robotics will be used to the maximum extent possible to allow samples to be collected from various locations around the landing site. This mission could serve as a precursor to a manned flight to Mars, which may take place later in the decade. This is a complex mission requiring Earth launch and transfer to Mars, capture of a spacecraft into Mars orbit, landing on Mars, launch of the sample carrier from Mars, rendezvous and sample transfer to the orbiting surface. This study included only transfer to Mars, insertion into Mars orbit, transfer from Mars orbit to craft, return to Earth orbit, and sample return to Earth's Earth, and insertion into Earth orbit. Descent to and ascent from the Martian surface were beyond the scope of this study.

Interstellar Probe

The Interstellar Probe is intended to analyze the interstellar medium. Our Sun's heliosphere shields us from the interstellar medium, so very little is known about the vast areas of space between stars. As it travels to the edges of the heliosphere, the Interstellar Probe will take data on heliosphere-interstellar medium interactions. The nominal performance target for this mission is to reach a distance of 200 astronomical units (AU) in twenty years or less. This requires a ΔV beyond Earth escape of about 60 km/s, assuming it is delivered in a couple of years or less. For 15-year trip times, the ΔV goes up to 70 km/s. Only the highest performance in-space propulsion systems are practical for this very demanding mission.

Solar Polar Imager

To fully understand the structure of the solar corona and to obtain a three-dimensional view of coronal mass ejections, observations from above the Sun's poles are required to complement data obtained from the ecliptic plane. Viewing the Sun and inner heliosphere from a high latitude perspective could be achieved by a solar polar imager in a Sun-centered orbit about one half the size of Earth's orbit, perpendicular to the ecliptic.

This mission requires a heliocentric plane change to go from a near-ecliptic orbit resulting from launch from Earth to an orbit inclined 45° or more to the ecliptic. It must also go close to the Sun -- to about 0.5 AU. The ΔV requirement is large, and favors high I_{sp} systems or those that derive thrust from solar interactions, such as solar sails.

Magnetospheric Constellation

The Magnetospheric Constellation mission intends to study the magnetotail of the Earth, which is the large magnetic field trailing Earth's orbit around the Sun. A constellation of 50 to 100 nanosatellites will be deployed in orbits around the Earth. These orbits have the same perigee at approximately 3 Earth radii (R_E), with varying apogees from 7 to 40 R_E, creating a distributed network of space weather observatories.

Pole-Sitter

This is an Earth Science Mission with cooperation between NASA, NOAA, and several other agencies to study sun-earth interactions causing the solar weather. These satellites will be part of a larger constellation around and between the Earth and the Sun in order to completely study all aspects of the Sun's influence on our planet. Two pole sitter satellites will be placed in orbits above each of the Earth's poles at a distance of approximately 100 earth radii. Since these are not Keplerian orbits, constant thrusting via advanced propulsion technology will be necessary to keep the satellites on station for the duration of the mission.

HEDS Mars Piloted

A manned trip to Mars is the natural extension of continued exploration of our solar system. Mission objectives include developing a better understanding of Mars both current and historically and to demonstrate the feasibility of future longer term Mars exploration and/or colonization. Manned launches would likely be combined with cargo launches to provide backup equipment and supplies for the first and future manned exploration missions. Mission payloads are large, ranging from 10s to 100s of tons. Mission delta Vs can be high, depending on mission profile. This mission requires high performance and much larger propulsion systems than other missions analyzed during IISTP.

Mission Analysis

A mission analysis was performed by the Systems Team for each mission. The purpose of the mission analysis is to define the important parameters related to the mission (examples), define the propulsion requirements, calculate important mission parameters for each candidate propulsion technology, and define important mission issues related to each propulsion technology. Transport from Earth's surface to low Earth orbit was represented by selecting among existing and planned commercial launch vehicles.

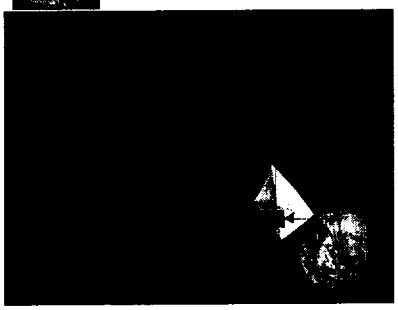
The Mission Analysis Team produced two products. The first was a one page summary of the important mission characteristics for each mission and each propulsion technology. These summaries were used as the basis of understanding of the application of the technology to the mission. Two examples of these summaries are shown in Figures 1 and 2. The second product was the scores as discussed below.

Technology Scoring

For any decision process, the process of making a rational selection among numerous candidates involves a two step process: (1) defining the important features, including defining their relative importance and (2) evaluating how each candidate performs for each important feature. Therefore, technology scoring for IISTP was a two-step process. The first step was the identification, definition, and weighting of figures of merit. Twenty-six figures of merit were identified as representing propulsion characteristics which may be desirable for each of the missions. A Figure of Merit (FOM) dictionary was generated to define each figure of merit and to give scoring guidelines related to each figure of merit. The Figure of Merit dictionary was provided to each of the enterprise representatives who defined the weight for each figure of merit on a scale of 0 (irrelevant) to 10 (highly important). Table 2 shows the figures of merit and the weights selected by each of the enterprise representatives. As shown later, the weights are only relevant within each FOM category.

The second step in the technology scoring process was the scoring of each technology for each figure of merit. Performance, Technical, and Reliability scoring was done by the Systems Team. The Cost Team did cost scoring, and the Technology Team did schedule scoring. Since the technology team was most familiar with each of the technologies, it was deemed that they were the most knowledgeable people for estimating the development schedule. Weights were withheld from the scorers so that there was little possibility that scorers could or would modify their results to affect outcome. For the Neptune Orbiter, there were 21

IISTP Science & Exploration Missions
Solar Sail Option to Earth Pole Sitter



- **Assessment Results**

– IMEsc:	1.64 mt	0.56 mt	0.25 mt
– Sail Technology	Worse	Nominal	Better
– Areal Dens (g/m²)	13	10	5
• Tech Projection (g/m²)	10	10	10
– Square Sail Side (m)	303	180	125
• Tech Projection (m)	300	300	300
– Distance from Earth	3.9 M km	3.9 M km	3.9 M km
– Departure:	2010	2010	2010
– Trip Time	(days)	(days)	(days)
– Arrival:	2010	2010	2010
– Mission Duration :	(Unlimited)	(Unlimited)	(Unlimited)
– Total Mission Ops Time:	TBD yrs	TBD yrs	TBD yrs
– No. Launches: 1 ea.	Delta IV Med	Delta II 7325	Tarus
– L/V Capability to C_3=0 (Less 10% margin)	2.34 mt	0.61 mt	0.26 mt

- **Issues**
  - Sail areal density and size easily meets 2010 technology projections
  - Volumetric storage of sail in L/V payload fairing
  - Achievable Sail areal density, size
  - Deployment; control, stability, dynamics

- Transportation Approach
  - Launch Vehicle delivers to C_3 = ~> 0
  - Sail deployed post escape, flies to L1
    - Sail deployment mech. = 25% of Sail mass (jettisoned after deployment)
  - Sail sits (hovers) at off-set position "above" L1 using light pressure to "levitate" against Earth's gravity
  - Unlimited time on station - no propellant used
  - Spacecraft (150 kg) remains attached to sail

Robert Frisbee / JPL
5/3/2001

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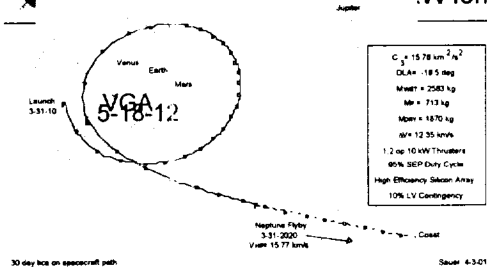
Figure 1. Sample of Results of System Analysis Showing Results of Solar Sail for Earth Pole Sitter

IISTP Science & Exploration Missions
SEP/Aero/Chem (10 kW Ion 5000 sec) Option to Neptune/Triton



- **Assessment Results**

– IMEsc:	2.58 mt
– Xe prop. Mass:	0.71 mt
– Power:	24 kW
– Departure:	March 31, 2010
– Neptune Arrival:	March 31, 2020
– Trip time:	10 yrs
– Total Mission Ops Time:	~13 yrs
– No. of Launches:	1 (Delta 4240)

- **Issues**
  - Grids development
  - High voltage propellant isolator development
  - Light weight engine body
  - 550-kg throughput demonstration
  - Wide 1-10 kW range throttling
  - Multi-engine demonstration
  - New PPU & DCIU development
  - Some advanced feed system components
  - Aeroshell /ballute mass fraction for high Vinf

- **Transportation Approach**
  - Launch to C3 = 15.7 km ²/s²
  - Venus GA 2 yrs after launch
  - SEP module jettisoned at ~ 3.5 AU
  - SEP module has 2+1 spare eng, 2+1 spare PPUs
  - Ballute or Aeroshell scaling fraction= 30%, V " @ Neptune = 15.8 km/s
  - Payload mass: 500 kg S/C, 246 kg Aeroshell, 75 kg Mono-prop.

M Noca/JPL
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Figure 2. Sample of System Analysis Showing Results for Solar Electric Propulsion for Neptune Orbiter

Table 2. Figures of Merit and Their Weights Assigned by the NASA Enterprise Representatives

FOM Category	FIGURES OF MERIT:	Earth Science	Space Science	HEDS
PERFORMANCE	Payload mass fraction	10	9	5
	Trip time	5	10	10
	Tine on station	5	0	0
	Prop. system launch mass & volume	0	10	1
TECHNICAL	Operational complexity	5	9	5
	Propellant storage time	5	9	5
	Station keeping precision	2	0	0
	Crew Productivity	0	0	5
	Sensitivity to malfunctions	8	10	5
	Sensitivity to performance deficiencies	7	10	5
	Enable in-space abort scenarios	2	0	7
	Crew exposure to in-space environments	5	0	3
RELIABILITY/ SAFETY	Pre-launch environmental hazards & protection	5	10	0
	In-space environmental hazards & protection	8	10	2
	Crew exposure & safety	0	0	8
	Payload exposure & protection	8	8	8
	Relative reliability assessment	8	10	10
	Operating life	7	10	0
COST	Technology advancement cost	8	9	2
	Mission non-recurring cost	8	9	10
	Operational cost	9	10	7
	Mission recurring cost	9	10	7
SCHEDULE	Total development time	5	10	10
	Special facility requirements	5	9	3
	Architectural fragility	5	9	5
	Maturity (TRL level)	5	8	10

technologies evaluated. Sample scoring for six of those technologies is shown in Table 3. For the Neptune Orbiter, the term "SEP 10kW/AC/Chem" means that 10 kW solar electric propulsion has been used for transportation to Neptune with aerocapture used to achieve orbit and Neptune and chemical propulsion used to raise the perigee of the orbit around Neptune after completion of the aerocapture. The other mission descriptions have similar meanings. For Nuclear Electric, all propulsion requirements are met by the Nuclear Electric technology.

Once mission analyses were completed, the scoring teams were provided with guidelines in the FOM Dictionary for scoring each of the candidate ISP technologies. Scores were assigned as 0, 1, 3, or 9 according to the method of the highly successful Kepner-Tragoe Method of decision making used throughout government and industry over the past forty years. A score of 9 states that the technology fully satisfies the requirements of the FOM. A score of 3 states that the technology mostly satisfies the requirements; a score of 1 states that the technology somewhat satisfies the requirements; and a score of 0 states that the technology does not at all satisfy the requirements of the FOM. Since it was deemed that all figures of merit had to be satisfied to some degree, a technology was eliminated if it scored 0 for any FOM. For each FOM, the FOM Dictionary gave guidelines by which that FOM should be scored as a 0, 1, 3, or 9. Over the years, the Kepner-Tragoe method has determined that this non-linear scale tends to make high performers stand out.

After scoring was complete, the normalized total was calculated for each FOM category as:

$$\textit{Normalized Total} = 100\frac{\sum_i W_i S_i}{9\sum_i W_i}$$

where W_i = weight of ith figure of merit,
S_i = score for ith figure of merit.

Table 3. Sample of Scoring for Neptune Orbiter (Six technologies shown out of 21 total technologies)

	FIGURES OF MERIT	Weight	SOA Chem/ AC/ Chem	SEP 5 kW AC/ Chem	SEP 10 kW/ AC/ Chem	Nuclear Electric Ion	Solar sails/ AC/ Chem	Mag-sail (M2P2) /AC/ Chem
Perform.	Payload mass fraction	9	1	9	9	9	3	9
	Trip time	10	3	9	9	3	3	9
	Time on station	0						
	Prop. system launch mass & volume	10	3	3	3	1	1	9
	Normalized total for Perform.		26.44	77.01	77.01	46.36	25.67	100.00
Technical	Operational complexity	9	3	3	3	9	3	3
	Propellant storage time	9	9	9	9	9	9	9
	Station keeping precision	0						
	Crew Productivity	0						
	Sensitivity to malfunctions	10	3	3	3	3	3	3
	Sensitivity to perf. deficiencies	10	3	3	3	9	3	3
	Enable in-space abort scenarios	0						
	Crew exposure to in-space environments	0						
	Normalized total for technical		49.12	49.12	49.12	82.46	49.12	49.12
Reliability/Safety	Pre-launch environmental hazards & protection	10	1	1	1	3	1	1
	In-space environmental hazards & protection	10	3	3	3	1	3	9
	Crew exposure & safety	0						
	Payload exposure & protection	8	9	9	9	1	3	9
	Relative reliability assessment	10	3	3	3	3	3	3
	Operating life	10	9	3	3	1	3	3
	Normalized total for reliability/safety		53.70	39.81	39.81	20.37	28.7	39.81
Cost	Technology advancement cost	9	3	3	3	1	3	1
	Mission non-recurring cost	9	3	3	3	1	3	3
	Operational cost	10	1	3	3	3	3	3
	Mission recurring cost	10	9	3	3	1	9	9
	Normalized total for cost		45.03	33.33	33.33	16.96	50.88	45.61
Schedule	Total development time	10	3	3	3	3	3	1
	Special facility requirements	9	9	9	9	3	3	9
	Architectural fragility	9	3	9	9	9	9	9
	Maturity (TRL level)	8	3	3	3	3	1	0
	Normalized total for schedule		50.00	66.67	66.67	50.00	45.06	53.09

If a technology scores the highest possible score "9" for each FOM within a FOM category, the normalized total for that technology for that FOM category is 100.

FOM Category Weights

The relative importance among the FOM categories was accounted for through the establishment and application of weights to the FOM category normalized scores. The establishment of FOM category weights was a very important aspect of the evaluation process. In the development of any system, there are primary objectives that reflect the purpose for which the system is to be developed, and there are supporting objectives that reflect the constraints under which the system will be developed.

Specifically, the overall objective of the IISTP effort was to recommend for investment the ISP technologies that can most effectively and economically perform the highest priority missions. The primary objective was ISP performance; those ISP technologies that can significantly reduce trip time and increase payload mass fraction for future space missions. In general, primary objectives support advanced technologies, while supporting objectives often support retention of current state-of-the-art technologies. Existing technologies inherently have less programmatic risk due in large part to their level of maturity and operating experience. Less programmatic risk usually results in state-of-the-art systems scoring better than advanced systems on reliability/safety, cost, and schedule FOM categories. Placing high weight on these FOM categories and on supporting objectives favors existing technologies and makes new technologies appear less attractive.

The IAG carefully considered FOM category weights to ensure the primary objectives and supporting objectives were properly accounted for in the final results. Performance was determined to be twice as important as cost for advanced ISP technologies. Cost and Technical were equally weighted and determined to each be twice as important as either reliability/safety or schedule. The resulting FOM category weights were:

Performance	40%
Technical	20%
Reliability/Safety	10%
Cost	20%
Schedule	10%

Cost-Effectiveness Analysis

It was desired to capture the spirit of a benefit/cost analysis, even though both benefits and costs were determined on a largely qualitative scale. To facilitate the evaluation of the candidate technologies based on their relative effectiveness and economics, two new parameters were defined:

Effectiveness Parameter - a measure of how well the candidate ISP technology reliably and safely performs the mission and meets the technical objectives. The Effectiveness parameter was computed as a linear combination of the normalized totals for performance, technical, and reliability/ safety FOM categories and their respective relative weights. It is expressed as:

$$E = 0.57\,p + 0.28\,t + 0.14\,r$$

where E = effectiveness parameter,
p = normalized total for performance,
t = normalized total for technical,
r = normalized total for reliability/safety.

The coefficients of 0.57, 0.28, and 0.14 were based on the FOM category weights discussed in the previous section. For example, the coefficient for p is 40/(10+20+40) = 0.57.

Cost Parameter - A measure of how economical the ISP technology is in terms of dollar cost and schedule considerations. The Cost Parameter is a linear combination of the normalized totals of cost and schedule FOM categories and is expressed as:

$$C = 0.67\,c + 0.33\,s$$

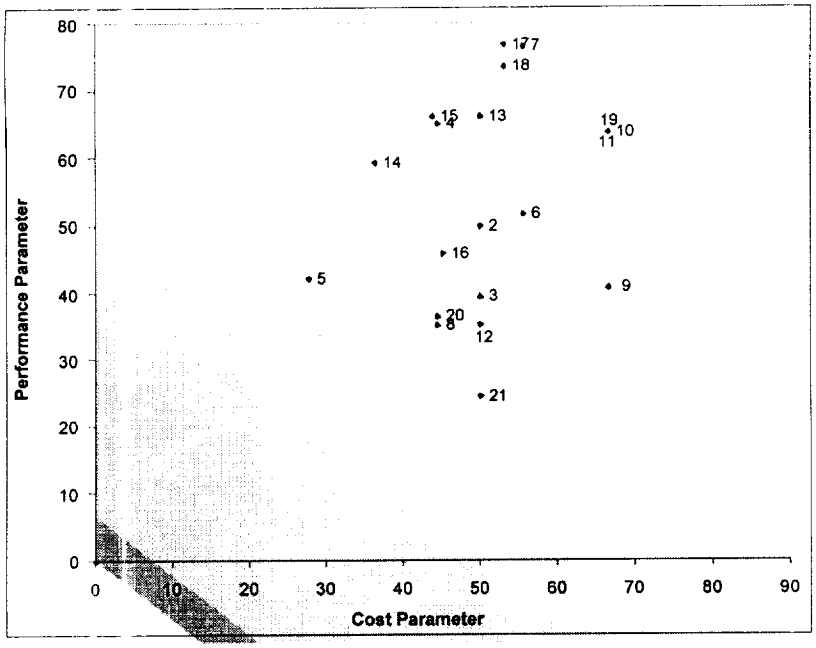
where C = cost parameter,
c = normalized total for the dollar cost,
s = normalized total for the schedule.

A high cost score represents low dollar cost and short schedule.

The effectiveness parameter was plotted against the cost parameter for each of the nine missions. Figures 3 through 7 show the results for the Neptune Orbiter, Titan Explorer, Mars Sample Return, Solar Polar Imager, and Interstellar Probe. The upper right corner of the plot represents high effectiveness and low cost and therefore represents the most desirable characteristics.

Conclusions for Investment Decisions

It was decided that the final prioritization should be a human responsibility, rather than the result of an automated process. Therefore, the responsibility for final prioritization of the ISP technologies was left to the IAG. Their responsibility was to examine the data for all nine missions and generate the prioritized list of technologies. During the analysis phase, nine missions were analyzed to evaluate more than 20 different propulsion system options against 26 figures of merit. The results were represented in approximately 20 different bar-line and scatter plots. Given the extensive amount of data generated, it was decided that the most efficient way to analyze the data and formulate a set of prioritizations was to convene the IAG face-to-face in an off-site workshop. The primary objective of the workshop was to identify a prioritized set of ISP technologies that could be used to guide investment decisions.



2 SOA Chem/AC/Chem
3 Adv. Chem/Chem
4 Nuclear Thermal/ AL
5 NTP bimodal/AP
6 MX tether/Augment/AP
7 MX Tether/Augment/AC/Chem
8 SEP Hall/NTP/AC/Chem
9 SEP HALL/Chme/AC/Chem
10 SEP (5 kW)/AC?Chem
11 SEP (10kW)/AC/Chem
12 NEP Hall/Chem/AC/Chem
13 NEP Ion
14 NEP VaSIMR
15 NEP MPD
16 Solar Sail/AC/Chem
17 Mag-Sail (M2P2)/AC/Chem
18 Mag-Sail (M2P2)/AP
19 Radio-isoptope Electric
20 NTP/NEP Hybrid
21 Solar Thermal Prop./AC

AP All Propulsion
AC AeroCapture
SOA State-of-the-art
MX Momentum Exchange
NEP Nuclear Electric Propulsion
NTP Nuclear Thermal Propulsion
SEP Solar Electric Propulsion

Figure 3. Cost-Effectiveness Scatter Plot for Neptune Orbiter

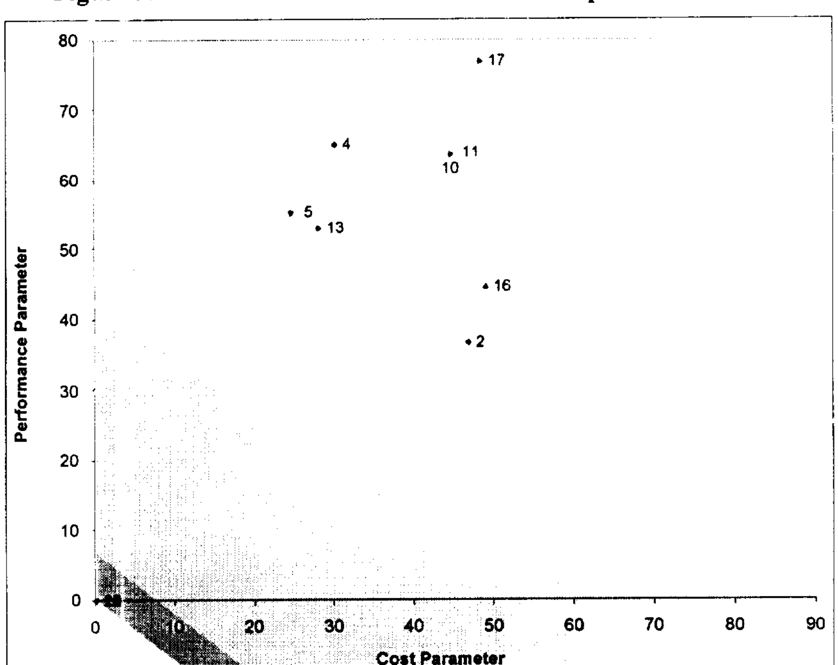


Figure 4. Cost-Effectiveness Scatter Plot for Titan Explorer

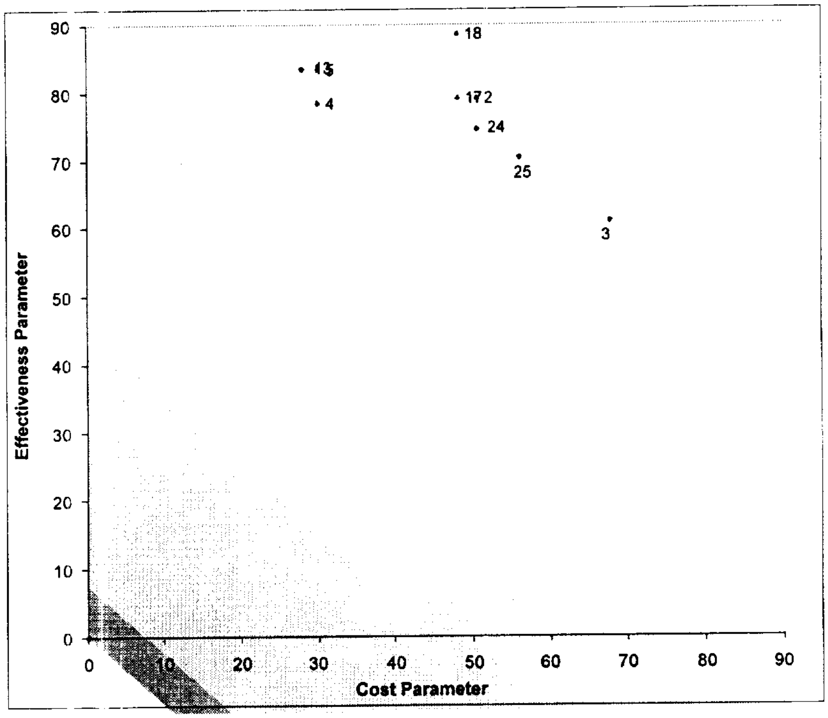


Figure 5. Cost-Effectiveness Scatter Plot for Mars Sample Return

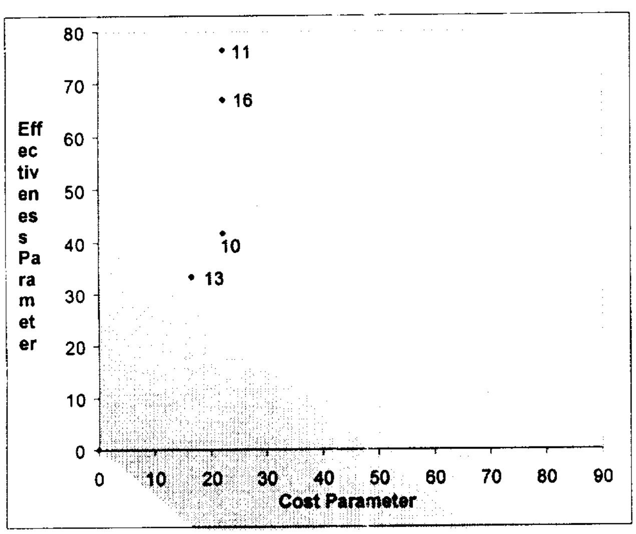


Figure 6. Cost-Effectiveness Scatter Plot for Solar Polar Imager

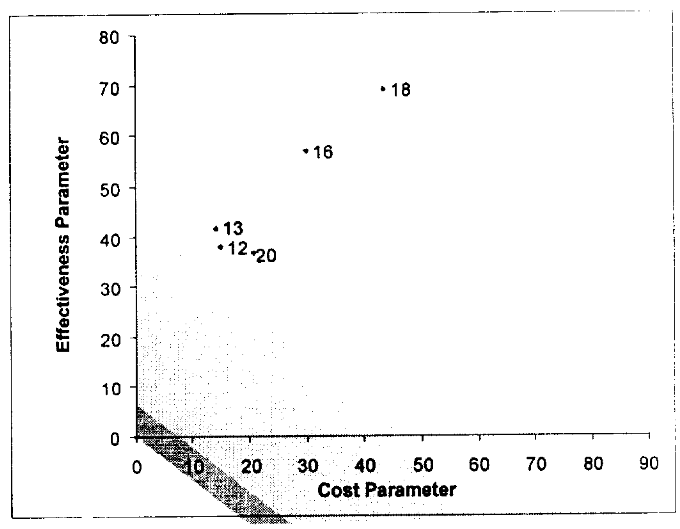


Figure 7. Cost-Effectiveness Scatter Plot for Interstellar Probe

Each technology was evaluated using the data and scores generated prior to the workshop. The primary objectives of the decomposition was to segregate these technologies according to how well they scored in the scatter plots. The scatter plots of overall performance versus overall cost measures were used extensively during the decomposition. Initially, technologies could be placed in one of three scoring bins:

1) Best in class: ISP technologies that scored highest on at least one of the nine missions analyzed.
2) Strong performer: ISP technologies that scored well (i.e., effectiveness parameter score greater than 50%) over a majority of the nine missions for which the technology was a viable candidate.
3) High Risk/High Payoff: ISP technologies that are considered to be high risk due to their low TRL, but have a potential for high payoff should they be developed.

The results of the decomposition are given in Table 4. Most of the propulsion technologies were classified as primary technologies. However, momentum exchange tethers and aerocapture were classified as supporting technologies. That is, they cannot be used for primary propulsion for a mission, but they can be used in an assist role to reduce the Delta V requirements of the primary propulsion technology.

The final strep in the workshop process was to combine all of the results into a cross-Enterprise prioritized set of ISP technologies that could be used to guide investment decisions. The IAG as a whole reached a consensus, and the results are given in Table 5.

Table 4. First Level Decomposition of Technologies for Prioritization

In-Space Propulsion Technology	"Best in Class"	"Strong Performer"	"High Risk/ High Payoff"
SOA Chemical (pivot)			
Advanced Chemical	MSR	EL	
Nuclear Thermal Propulsion		NO, MSR, TE, MP	
Bimodal NTP		MSR, MP	
Momentum Exchange Tethers	NO, EL		X
Solar Electric Hall	MP, MC		
Solar Electric Ion	NO, TE, MSR, EL, PS	MC, SPI	
Nuclear Electric Hall			
Nuclear Electric Ion		MSR, MP, NO, TE, EL	
Nuclear Electric VaSIMR		NO	
Nuclear Electric MPD		NO++	
Solar Sails	SPI, PS		
Solar Sails (1 gm/m^2)	ISP		X
Plasma Sails	NO, ISP, MSR, EL, TE		X
Solar Thermal Propulsion		MC	
NTP/NEP Hybrid			
Aerocapture	NO, MSR, TE, MP		

EL - Europa Lander, ISP - Interstellar Probe, MC - Magnetospheric Constellation, MSR - Mars Sample Return, MP - Mars Piloted, NO - Neptune Orbiter, PS - Pole Sitter, SPI - Solar Polar Imager, TE - Titan Explorer

Table 5. Final Prioritization of Technologies for IISTP

HIGH	MEDIUM	LOW	HIGH PAYOFF/ HIGH RISK	DROP
Aerocapture	Solar Sails	Solar Thermal Propulsion	Plasma Sail (M2P2)	Nuclear Thermal Propulsion
Solar Electric Propulsion Ion (5, 10 kW)	Solar Electric Propulsion, Hall Thruster (100 kW)	Bimodal Nuclear Thermal Propulsion (low to high power scalable)	Momentum Exchange Tether	
Nuclear Electric Prop. (low to high power scalable)	Class I Electric Propulsion (30-100 kW)		Solar Sail (1 gm/m^2)	
	Advanced Chemical			
	Class II Electric Propulsion (100-500 kW)			