

INTERSTELLAR EXPLORATION: PROPULSION OPTIONS FOR PRECURSORS AND BEYOND

Les Johnson

*Manager, Interstellar Propulsion Research
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama USA*

Stephanie Leifer

*Advanced Propulsion Technology Group
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California USA*

Abstract

NASA is considering missions to explore near-interstellar space (40 – 250 Astronomical Units) early in the next decade as the first step toward a vigorous interstellar exploration program. A key enabling technology for such an ambitious science and exploration effort is a propulsion system capable of providing fast trip times, yet which has low enough mass to allow for the use of inexpensive launch vehicles. Advanced propulsion technologies that might support the first interstellar precursor mission by the end of the first decade of the new millennium include solar sails and nuclear electric propulsion. Solar sails and electric propulsion are two technology areas that may hold promise for the next generation of interstellar precursor missions as well – perhaps a thousand astronomical units traveled in a professional lifetime. Future missions to far beyond the Heliosphere will require the development of propulsion technologies that are only at the conceptual stage today.

For years, the scientific community has been interested in solar sail and electric propulsion technologies to support robotic exploration of the solar system. Progress in thin-film materials fabrication and handling, and advancement in technologies that may enable the deployment of large sails in space are only now maturing to the point where ambitious interstellar precursor missions using sails can be considered.ⁱ Xenon ion propulsion is now being demonstrated for planetary exploration by the Deep Space 1 mission. The primary issues for the adaptation of electric propulsion to interstellar precursor applications include the development of low specific mass nuclear power systems, engine lifetime, and high power operation.

Recent studies of interstellar precursor mission scenarios that use these propulsion systems will be described, and the range of application of each technology will be explored.

1.0 Introduction

Voyagers I and II are well on their way to being the first interstellar emissaries of the human race. Launched in 1977 on a mission to explore the outer planets, the Voyager I spacecraft is now traveling at 37,000 kilometers per hour on its way out of the solar system and into the heliopause - the boundary between the end of the Sun's magnetic influence and the beginning of interstellar space.ⁱⁱ On-board instrumentation is still functioning and

returning useful scientific data because of the radioisotope thermoelectric generator (RTG) power source providing heat and power.

In the 22 years since its launch, the Voyager I spacecraft has traveled over 6.5 billion miles from Earth. Voyager acquired the kinetic energy for its journey through a combination of gravity assist maneuvers using planets it visited during its tour of the solar system, and from its chemical thrusters. While Voyager is a tremendous achievement, it will take many more years or even decades to reach the outer boundary of the sun's influence. Furthermore, the spacecraft will take another 74,000 years to travel the distance between our solar system and our nearest neighboring star.

In October of 1998 a new era arrived in propulsion technology with the launch of NASA's Deep Space 1 mission. DS1 carries an ion engine - a device that operates at a specific impulse roughly 10 times that of Voyager's engines. The high specific impulse of ion engines will enable many of the exciting new deep space robotic missions whose propulsion requirements are too difficult, and therefore too expensive, to be met with traditional chemical thrusters. Such missions include outer planet orbiters, landers, and even sample-return missions.

However, ambitious future missions into deep space will require propulsion systems capable of imparting much greater momentum to spacecraft than chemical thrusters, gravity assists, or even today's ion engines can deliver. These missions include fast robotic voyages into interstellar space.

In early 1999, NASA's Office of Space Science convened a mission science and technology definition team to explore the possibility of sending a robotic probe to the edge of our solar system and beyond. The team developed a preliminary set of objectives for such a mission, should it be approved for flight sometime in the future. They areⁱⁱⁱ:

- Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and the Universe.
- Explore the influence of the interstellar medium on the solar system, its dynamics and its evolution
- Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment
- Explore the outer Solar System in search of clues to its origin, and to the nature of other planetary systems.

The Voyager I spacecraft cannot meet these science objectives because it is not carrying many of the scientific instruments needed to explore the interstellar medium. Furthermore, long before Voyager I reaches the outer boundary of the sun's influence, in around 2020, the available electrical power will no longer support science instrument operation. At that time science data return and spacecraft operations will end.

To achieve the objectives of the Interstellar Probe Science and Technology Definition Team (ISP-STDT) within the professional lifetimes of the investigative team (20-30 years), a suite of instruments aboard a small spacecraft will need to travel further and faster than

any spacecraft flown previously. A mission goal of reaching 200 Astronomical Units within 15 years of launch was established.

Shortly after the first interstellar mission study was initiated, a second study to explore the possibility of performing a rendezvous mission with a Kuiper Belt Object also began. The Kuiper Belt preserves a relatively pristine mix of solar nebula and interstellar material. Thus, the Kuiper Belt Object Rendezvous mission is motivated by an interest in the origins of our solar system. Propulsive requirements for the KBO mission are even more demanding than the Interstellar Probe mission because large delta-V maneuvers are required late in the mission to affect a rendezvous.

2.0 Advanced Propulsion Technology for Interstellar Precursor Missions

A preliminary evaluation was made of several propulsion options to determine the performance capability of each for delivering a science payload to the heliopause and for rendezvousing with a Kuiper Belt Object. The options included an all-chemical approach with planetary gravity assists, chemical with planetary aero-gravity assists, solar sails, and electric propulsion. The principal parameters driving the evaluation of candidate propulsion options were achievable mission Delta-V, propulsion system mass, and payload delivery capability. It was assumed that the propulsion technology would be available by the end of the first decade of the new millennium. Thus, other more exotic advanced propulsion concepts were not considered.

Only two of the options - solar sails and nuclear electric propulsion - could meet the mission requirements in the timeframe of interest. The options considered and the qualitative trades between them are described in Table 1.

With the successful flight of the solar powered ion propulsion system on the Deep Space 1 mission, and the numerous electric propulsion systems in use by Earth orbiting spacecraft, it is now possible to consider the use of electric propulsion for more ambitious deep space applications. However, solar power is not a feasible option for an electric propulsion system on a fast mission into interstellar space – the spacecraft does not spend enough time close to the sun to build up adequate velocity. For example, a rendezvous mission to the outer solar system such as the KBO mission would require a solar collector with a mass estimated to be on the order of 50,000 kg [ref Nesmith] in order to collect enough power for an 11 year trip time with electric propulsion. Given the relatively high power levels required to achieve fast trip times, a small fission reactor capable of producing tens of kilowatts of power would be ideal.

Electric thrusters for interstellar precursor missions will have to operate at substantially higher specific impulse (approximately 9,000 to 14,000 seconds, depending upon the mission) to achieve desired trip times. Engine component lifetime at the required beam voltages will require development. Furthermore, the large amounts of propellant required lead to the use of krypton as a more economical alternative to xenon, the current propellant of choice for ion thrusters.

Prop. System	Interstellar Probe Mission to the Heliopause		Kuiper Belt Object Rendezvous Mission	
	Benefits	Issues	Benefits	Issues
Solar Sails	<ul style="list-style-type: none"> • Propellant-free propulsion • Promising new technology developments • Potential for low overall s/c mass • Potential for high delta-V/fast trip time (10-20 AU/year) • Technology has broad applications for deep space robotic exploration • Potential to integrate sail structure and other s/c functions 	<ul style="list-style-type: none"> • Immature technology • Control/stabilization • Deployment issues • Sail attitude control, TCMs • Sail emissivity/reflectivity vs. solar perihelion distance (thermal) • Loaded areal density vs. sail size and acceleration • Possible Science impact • Method favors small s/c mass • Radioisotope Launch Approval Process required (high curies at launch) 	<ul style="list-style-type: none"> • N/A 	<ul style="list-style-type: none"> • Option not viable for Rendezvous missions with fast trip time
Electric Propulsion	<ul style="list-style-type: none"> • Broad applicability to high delta-V missions • Some EP flight heritage • Extra onboard power for data return, extended missions • Propulsion capability deep into mission • Cold reactor at launch (low curies) 	<ul style="list-style-type: none"> • Engine lifetime • Higher ISP - effect on Power Processing Unit (PPU) mass • Science impact of Thruster plumes, Solar concentrator or Reactor • Not well suited for small payloads • Nuclear fission power required/necessitates both NEPA compliance and the Launch Approval process 	<ul style="list-style-type: none"> • Broad applicability to high delta-V missions • Some EP flight heritage • Extra onboard power for data return, extended missions • Propulsion capability deep into mission • Potentially high payload mass • Ability for rendezvous, SRM • Cold reactor at launch (low curies) 	<ul style="list-style-type: none"> • Nuclear fission power required. necessitates both NEPA compliance and the Launch Approval process • Engine lifetime • Higher ISP - effect on PPU mass • Possible science impact <p>For SEP:</p> <ul style="list-style-type: none"> • Concentrator/reflector technology - High CR implies need for good shape control - serious mass impact compared to solar sail. Very large (km scale). • 100 kW of high-temp., cosmic-ray rad-hard, long-life cells • Many of the same issues associated with NEP.
Chemical w/Gravity Assist	<ul style="list-style-type: none"> • Least propulsion system technology development required. 	<ul style="list-style-type: none"> • Longer trip times • More restricted by launch windows for GA trajectories • Does not develop propulsion technology for use in other space exploration missions • Earth flybys w/RPSs complicates required reentry safety analysis • Restricted to small payload mass 	<ul style="list-style-type: none"> • Least propulsion system technology development required. 	<ul style="list-style-type: none"> • Very long (>30 year) trip times required for modest payload. • Requires launch approval for RTGs (high curies at launch) • More restricted by launch windows for GA trajectories • Does not develop propulsion technology for use in other space exploration missions • Earth flybys w/RPSs complicates required reentry safety analysis • Restricted to small payload mass

Chemical w/Aero-gravity Assist	<ul style="list-style-type: none"> •Potentially higher Delta-V than chemical/GA option, fewer assist maneuvers (use VAGAMAGA). 	<ul style="list-style-type: none"> •Waverider concept requires technology development •TPS, s/c control during assist •Technology not extendible to more ambitious missions •Radioisotope Launch Approval Process required 	<ul style="list-style-type: none"> •Potentially higher Delta-V than chemical/GA option, fewer assist maneuvers (use VAGAMAGA). 	<ul style="list-style-type: none"> •Waverider concept requires technology development •TPS, s/c control during assist •Technology not extendible to more ambitious missions •Radioisotope Launch Approval Process required (high curies at launch)
--------------------------------	---	--	---	--

Table 1. Propulsion options considered for Interstellar Probe and Kuiper Belt Object Rendezvous Missions.

In addition to electric propulsion, solar sailing (use of solar photon momentum exchange) offers a propulsion method for delivering robotic spacecraft to many deep space destinations in the next decade. Developments in thin films, combined with other materials science breakthroughs of the last ten years, make large-diameter sails for spacecraft propulsion a promising technology. The Russian Znamya program which has deployed spinning solar sails from Progress vehicles and the Inflatable Antenna Experiment deployed from the Space Shuttle in 1996 are two examples of recent space demonstrations of solar sail and solar sail component technologies.

The primary performance parameter for solar sails is their areal density (grams/m²) which determines the acceleration of the sail (i.e., solar pressure [N/km²] divided by areal density [g/m²] gives acceleration). The thickness and density of the sail material determine areal density, and the mass of the supporting structure. The term “loaded areal density” refers to the entire sailcraft mass, including payload, divided by sail area. Solar sail areal density requirements range from around 20 grams/m² to perform near-term demonstration missions to around 1 gram/m² to accomplish fast missions to the heliopause.

Operating temperature is another figure of merit for solar sails, as it dictates minimum solar perihelion distance and therefore maximum achievable acceleration for a given sail areal density. Maximum operating temperature is governed by the sail materials, reflectivity, and emissivity.

Sailcraft survivability also merits serious consideration by mission planners. Understanding sail performance degradation over time due to space environmental effects – micrometeoroid impacts, radiation, and sail charging - will be critical for successfully completing sail missions.

3.0 Interstellar Precursor Mission Studies

3.1 Interstellar probe – a mission to the Heliopause and beyond

The Interstellar Probe Science and Technology Definition Team set an interstellar probe mission start date in the 2007 time frame, with a launch around 2010. The mission design life is 15 years to get to 200 AU with a 15-year hardware design life. However, total mission duration of approximately 30 years to get to 400 AU would be possible based on consumables.

3.1.1 The Baseline Mission- Solar Sail Propulsion

One option for meeting the propulsion requirements of the ISP mission is to use a solar sail, which would be deployed shortly after launch. The main thrust-vector control (TVC) functions during the solar sail acceleration period would be accomplished by furling and unfurling the sail. One or more chemical propulsion systems would also be required for miscellaneous TVC requirements.

The baseline solar sail design assumes a spin-stabilized structure with an areal density of 1g/m^2 (including film and structure), and a diameter of approximately 400-m with an 11 meter wide central opening. The spacecraft module would be centered in the 11-m-diameter central aperture of the sail. The total spacecraft module mass supported in the sail would be approximately 180 kg. For sail attitude control and thrust vector pointing, it is planned to move the spacecraft off-center with booms that extend to the edge of the sail. It has been roughly estimated that a meter or two shift of the spacecraft will provide enough torque to precess the spacecraft the required 8° per day when the spacecraft flies by the sun.

The sail craft would be used on a heliocentric trajectory from Earth escape inbound to a 0.25 AU perihelion, then outbound to 5 AU, where the sail would be jettisoned to minimize interference with science acquisition and communication. A previous study on the use of solar sails for interstellar precursor missions proposed an "H-reversal trajectory" [ref Vulpetti]. This trajectory was examined and was not found to offer a performance benefit in comparison with the one used in this study^{iv}.

A single Delta II class launch vehicle would be used to deliver the sail-craft to an Earth-escape trajectory. A total impulse requirement of approximately 1,800 N-s is needed to spin the spacecraft during initial unfurling of the sail. Initial spin rate of the vehicle would be on the order of 12 to 15 rpm. It should be noted that the solar sail deployment design requires a 12-rpm initial spin rate to provide the centrifugal force required to pull the sail radially outwards. The system for initial spin-up during solar sail unfurling includes four simple, helium cold-gas systems each located at the end of long (30-m) booms.

Once the solar sail has deployed, the combined spin up mechanism (boom assembly and empty RCS systems) and deployed solar sail/spacecraft will be spinning at a desired 0.3 rpm spin rate required to provide enough radially acceleration to force the sail outwards. Once deployment is complete, excess deployment system mass (including launch vehicle interface structure, sail canister, four balancing booms and cold-gas attitude control system) will be jettisoned and the spin-stabilized solar-sail spacecraft can begin its mission.

After reaching 5 AU, the solar thrust available from the sail will become rather low. At this point the sail will be separated. The high inertia of the sail will assure that it will change attitude very slowly, giving an easy spacecraft separation from a small spring-driven separation system. The final coast velocity of the system could exceed 14 AU/year.^v The trajectory can be seen in Figure 1.

A second option was considered that would use a larger solar sail, and also travel closer to the sun (0.2 AU instead of the baselined 0.25 AU). This larger solar sail option, with a

high-performance sail with 0.75g/m^2 areal density and 600 m diameter, would reach a higher velocity and shorten the time required to get to 200 AU. With this option, the spacecraft structure would be little changed from the baseline design. The primary impact identified for propulsion was that the spacecraft inertia would increase considerably as a result of the larger sail, directly impacting the initial spinning function with the cold-gas system on the end of the booms. The angular momentum would increase by a factor of 13. It was assumed that the increase could be compensated with longer booms and/or more mass at the end of the booms. Employing a 600-m sail significantly increases the spin-axis inertia to roughly $5 \times 10^6 \text{ kgm}^2$. This results in 35-m booms and four to five times more fuel for the initial angular momentum build-up.

3.1.2 Other Propulsion Options Considered

3.1.2.1 Chemical propulsion with Gravity Assist Maneuvers

A previous mission study for an interstellar probe was conducted by Mewaldt et al^{vi}. The mission scenario examined in that study was to send a 200-kg spacecraft with a 27-kg instrument package to a heliocentric distance of 200 AU in a trip time of 25 years or less. Because nuclear electric propulsion and solar sails were technologies deemed unavailable at the time of the study, chemical propulsion with planetary gravity assist maneuvers was chosen for primary mission Delta-V. Trajectories for gravity assist (GA) trajectories using Jupiter (J), the Earth (E), Venus (V), and powered solar flybys (S) were considered in the combinations of JGA, JSGA, EJGA, EJSGA, and VEEJSGA. However, JGA and JSGA trajectories were found to provide inadequate performance and were not examined further. Both single and two-stage post launch propulsion options were considered.

Launch vehicle options considered were the Delta II, Atlas IIAS with a Star 48B, and the Titan IV/Centaur. The conclusion of the study was that an Atlas could deliver a small (200 kg) spacecraft with on-board chemical propulsion to 200 AU in approximately 25 years with a launch in the first decade of the new millennium.

The all-chemical with gravity assist propulsion option requires no new propulsion technology developments that would be enabling for other missions of interest on the NASA roadmap. It would not allow for final mission velocity in excess of 14 AU/year (with the Titan IV/Centaur), and would spend the first 5-10 years of the mission in the inner solar system performing planetary and solar flybys. Furthermore, the trajectory options considered would require an Earth flyby with radioisotope power supplies on board the spacecraft, complicating the required reentry safety analysis. For these reasons, the all-chemical option was not selected as the baseline propulsion system for the Interstellar Probe mission study.

3.1.2.2 Chemical propulsion with Aero-Gravity Assist Maneuvers

Chemical propulsion with aero-gravity assist was briefly evaluated to determine whether significant trip-time savings could result over chemical propulsion with standard gravity assist maneuvers. In an aerogravity assist, the spacecraft is configured as a lifting body; it derives a downward lift in a planetary atmosphere, thereby increasing the deflection of its flight path. A combination Venus Aerogravity Assist Mars Aerogravity Assist (VAGAMAGA) trajectory has been projected to result in up to 10 AU/year final spacecraft

velocity^{vii}. However, this option does not provide a sufficiently attractive total Delta-V capability to warrant the investment in the required technology developments for this application alone.

3.1.2.3 Nuclear Electric Propulsion

Nuclear electric propulsion (NEP) is the only propulsion option other than solar sails that both could be brought to a sufficiently high technology readiness level (TRL) and provide fast (10-15 year) trip times to the heliopause in the time frame of interest. Both Radioisotope Thermoelectric Generator (RTG) –powered electric propulsion and UZrH reactor power sources were evaluated. It was found that even advanced radioisotope power systems (ARPS) would have too high a specific mass ($> 60 \text{ kg/kWe}$]put in right ref) to allow the desired vehicle acceleration. Therefore, the evaluation of nuclear electric propulsion systems for a heliopause mission focused on an advanced reactor-based concept with total power plant specific mass well below 30 kg/kWe . Reactors are essentially non-radioactive at launch. The launch approval process is similar to that for Radioisotope Power Systems (RPS).

A nuclear electric propulsion system would use a 100-200 kWe nuclear reactor, launched “cold” – where only zero power testing has been conducted. The reactor would be activated at a positive C3 (beyond Earth escape) to power a Krypton-fueled ion propulsion system. The propulsion system would carry the Interstellar Probe science payload on an indirect trajectory (heliocentric spiral trajectory), building up to final velocity of approximately 25 AU/year after a 10 year run time. After engine burnout, the science payload would be deployed. The high power NEP spacecraft segment would then be used for a high gain data relay. Payload mass was studied parametrically from 50 kg to 250 kg, and trip times to 250 AU ranged from 16 to 20 years. Atlas III, Delta IV, and Proton Launch vehicles were considered. Figure 1 shows an example plot of the required nuclear reactor specific mass as a function of payload mass and trip time to 250 AU.

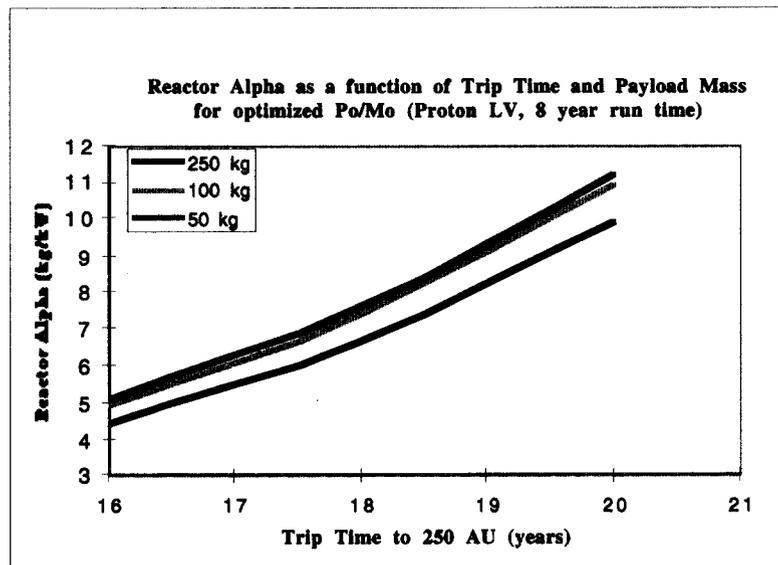


Figure 1. - Reactor Specific Mass as a function of payload mass and trip time for and NEP mission to 250 AU.

The spacecraft configuration chosen had the power and propulsion module separated from the main bus/science payload (spinning and decoupled from rest of spacecraft) by a 30-meter boom. Boom length was determined by the radiation shielding requirement and radiator area. The stowed configuration considered would fit within Delta III, Atlas II, Proton, and Titan IV fairings.

The reactor concept chosen for the ISP study was based on the U.S. Department of Energy's SNAP design. SNAP-10A flew in space and operated for 43 days before its voltage regulator malfunctioned and triggered an automatic shutdown. It produced 40 kW of thermal power and 0.5 kWe of electrical power via solid-state thermoelectric (TE) converters at 1.3 % total efficiency. It was very compact because it used UZrH fuel that rapidly slows down fission neutrons so that they may react with the uranium more easily. This fuel allows a minimum reactor size and U-235 mass to reach criticality. This fuel also allows a minimum shield mass because slowed "thermal" neutrons are easier to stop in a shield, and the small reactor size allows a small shield diameter.

The SNAP design results in intrinsically smaller and lighter reactor and shield systems than the SP-100 space nuclear reactor - America's most recent space reactor power program. The SP-100 program developed detailed designs, advanced reactor fuel, and component hardware, but was terminated before fielding either a ground test assembly or a space flight system. The SP-100 was designed to produce 100 kWe with a lifetime of 7 years at full power operation to 10 years total duration in space. It used a high-temperature advanced fuel (UN) which was developed and proven with nuclear burn-up tests during the program. The fuel was not designed to slow down the fission neutrons, so the neutron spectrum was "fast" and the resulting minimum size and U-235 mass for the reactor to achieve criticality was thus larger than for the SNAP series.

The thermal to electric power conversion would be accomplished through the use of a steam or toluene Rankine conversion system. Rankine systems are a highly mature technology with an extremely large industrial and extensive experience with reactor systems, particularly steam Rankine systems. The Rankine system obtains superheated vapor from a NaK-steam or toluene steam generator. The steam temperature would be between 673 K and 693 K. The steam is directed toward the turbine wheel through a series of nozzles. These nozzles can be isolated to provide optimal conversion efficiency at large turn-down ratios for coast and science missions. The use of recently developed lightweight deployable radiators was also assumed.

The ion propulsion system considered for the Interstellar Probe Mission would be comprised of 8 25 kWe krypton ion engines arranged in pairs with shared neutralizers. The engine design is tailored to meet the optimized specific impulse dictated by the mission trajectory, and may be between 12,000 and 14,000 s. A 10-year engine lifetime would be achieved through the use of sputter erosion-resistant carbon-carbon grids and low flow cathodes. Engine efficiency of 75% to 80% (as a function of specific impulse) was projected.

NEP system mass estimates included the ion engines, propellant feed system, propellant tankage and refrigeration, power processing unit (PPU), power conversion system, PMAD, reactor, shielding, and radiator mass. Because nuclear reactor specific mass decreases for increasing power level, a target power level of 100 kWe was chosen to obtain good performance.

Nuclear electric propulsion technology is well suited for delivering large payloads to destinations such as the heliopause, or for performing rendezvous and sample return missions where a large Delta-V is required far from the sun. The interstellar probe mission requires neither of these; as a flyby mission delivering a modest payload mass of approximately 180 kg, this mission can be accomplished with solar sail technology, thus avoiding the sensitivity associated with space nuclear power. However, an investment in the technology development for NEP deep space missions could also benefit the interstellar probe mission to the heliopause, particularly if future, follow-on missions required rendezvous or sample return trajectories. Furthermore, NEP represents a fallback technology should solar sails present unanticipated challenges to implementation. They also provide the option of increased scientific payload size.

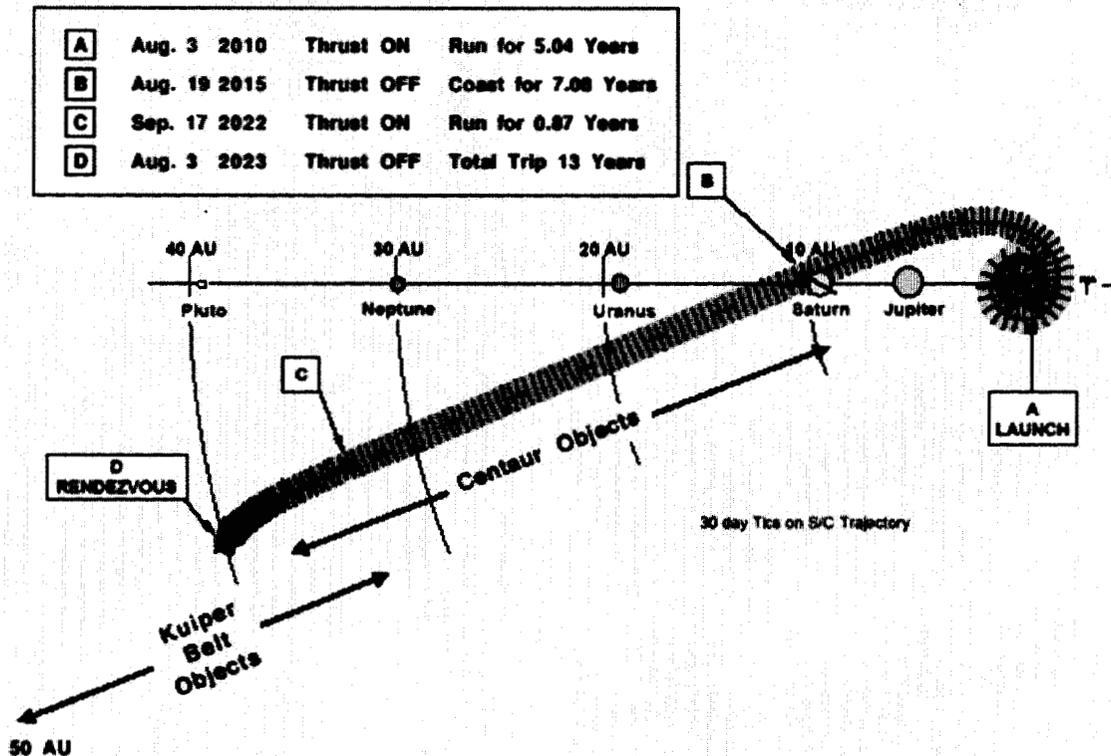
3.2 Kuiper Belt Object Rendezvous Mission

Concurrent with the Interstellar Probe mission study, NASA also was examining a mission scenario for performing a rendezvous mission with one or more Kuiper Belt Objects (KBO). The KBO Rendezvous mission includes cruise science with dust analysis, a Centaur object flyby, and orbital and in-situ measurements at two KBOs; scientific instrumentation is carried on both the carrier and the landers. Unlike a mission to the heliopause, the science requirements of the KBO mission would necessitate large propulsive maneuvers far from the sun and a very large (approximately 974 kg) science payload mass. In this scenario, nuclear electric propulsion was considered as the only viable option. The baseline mission characteristics are to launch in 2010 from a Delta IV Heavy, and begin returning science data within 5 years of launch. The goal is to reach 40 AU in 10 to 20 years. After arrival at the Kuiper Belt, the spacecraft would release a lander to a large KBO. After operations at the large KBO, the spacecraft will search for a smaller body, affect a rendezvous and deploy another lander.

3.2.1 Nuclear Electric Propulsion Flight System

In the baseline scenario, the Delta IV Heavy launch vehicle injects the spacecraft to Earth escape, which eliminates the need for an earth escape spiral or nuclear-safe orbit basing prior to nuclear reactor startup.

A 13-year flight time trajectory is depicted in Figure 3. The Delta IV Heavy lift capability to a Earth escape is 8435 kg. The spacecraft thrusts for 5 years, coasts for 7 years, then thrusts in the opposite direction for a year. Total thrust time does not include the time required to maneuver near a KBO and travel between objects (approximately 2 years).



Robert H. Frisbee, Data Courtesy Jon Sims/Julie Kangas

KBO Explorer - 6

Figure 2 – Thirteen year flight time trajectory for Kuiper Belt Object Rendezvous Mission

After arrival in the Kuiper Belt, the spacecraft will, with NEP, rendezvous within 250 km of a large KBO (defined as having a diameter of 500 km) and release the larger of the landers. After data collection and operations, the spacecraft will search for a small object (defined as having a diameter of 1 km). A smaller lander will be released after rendezvous with it.

The basic propulsion system for the main spacecraft consists of a Nuclear Electric Propulsion system with an approximately 100-kW nuclear-electric power system using krypton ion thrusters. The current design, when fully deployed, would place the reactor at one end of a 25-m truss. Next to reactor is the shielding, which gives an oval-shaped zone to shelter the rest of the system. Directly behind the shield is the conversion unit that powers the spacecraft. The conversion unit is followed by the two krypton propellant tanks and eight 60-cm-diameter electric propulsion units. Connecting the power area with the spacecraft bus is a fully extended 25-m truss from which two large radiator units are extended. Before launch, the 25-m truss is telescoped and the large radiators are folded to provide a compact volume for the launch vehicle. The entire system is launched using only the lander ARPS for deployment and reactor startup.

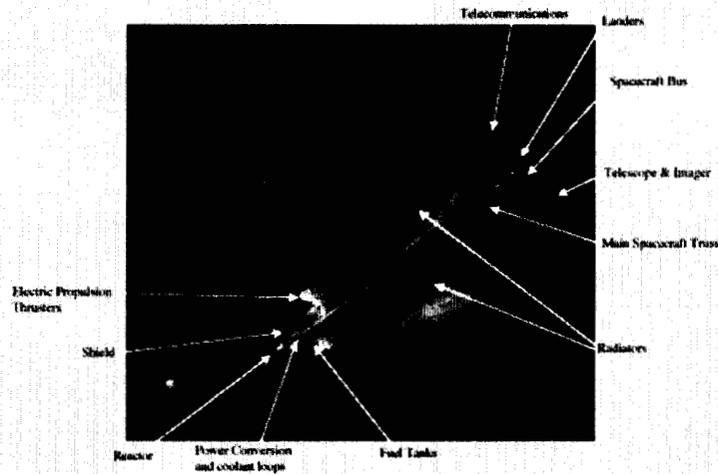


Figure 3. – Configuration of the KBO Rendezvous Mission NEP spacecraft.

The primary elements of the NEP system consist of two cylindrical aluminum propellant tanks (including active refrigeration and insulation), a feed system based on the NASA Space Technology 4 (Champollion) design, eight ion thrusters, eight power processing units (PPUs), and a single DCIU. The propulsion system mass was 3703.8 kg (including 522.8 kg of dry mass and 3181.0 kg of krypton). The selected ion thrusters design was derived from NSTAR - Deep Space 1 technology, with improved performance assumed from either new or already tested technologies. Table 2 summarizes the thruster performance assumptions. The design calls for a 25.3-kW thruster with an active beam diameter of 60 cm. The total power level dictates four operating thrusters at all times, but a total of eight thrusters are required to process the total krypton propellant load. The nuclear power system designed for the interstellar probe mission study is virtually the same one assumed in the KBO study. However, larger reactor specific mass was assumed for the latter. A separate cold gas GN2 system was added to the spacecraft to provide the necessary RCS functions when the NEP system is not in operation.

Power/thruster	25.3 kW
Propellant	krypton
Beam voltage	5300 V
Beam current	2 A
Accel voltage	935 V
Discharge loss	300 eV/ion
Discharge propellant efficiency	0.88
Flatness parameter	0.4
Maximum electric field	2000 V/mm
R-Ratio	0.85
Neutralizer flow rate	0.125 mg/s
Total flow rate/thruster	4.58 mg/s
Specific impulse	9475 s
Thrust/thruster	416 mN
Efficiency	0.75
Propellant throughput/thruster	500 kg
Mass/thruster	25 kg

Table 2. Ion Propulsion System Characteristics for the KBO Rendezvous Mission Study.

3.2.2 Other Propulsion Options Considered

Two alternative propulsion system candidates were selected for evaluation – ballistic chemical trajectories with gravity assists and a solar concentrator for modified solar electric propulsion.

For the chemical propulsion trajectories, the study assumptions were that there must be a delivered mass of at least 1000 kg, and that a Delta IV Heavy Launch Vehicle would be used. A flight system specific impulse of 350 s was assumed. It was found that direct trajectories could not deliver any payload mass to the desired rendezvous distance using the launch scenario of this study. Jupiter gravity assists alone would transfer half of the required mass in 50 years, while a triple-Venus and Jupiter gravity assist (VJVJGA) trajectory could deliver the desired mass, but in a 40 year trip time. The shortest trip times of 36 and 33 years were afforded by double-Venus, Earth and Jupiter gravity assists (VVEJGA) and double-Venus, Earth, Jupiter gravity assists with a powered solar flyby (VVEJSGA), respectively. None of these options meet the flight time constraint desired by the mission planners.

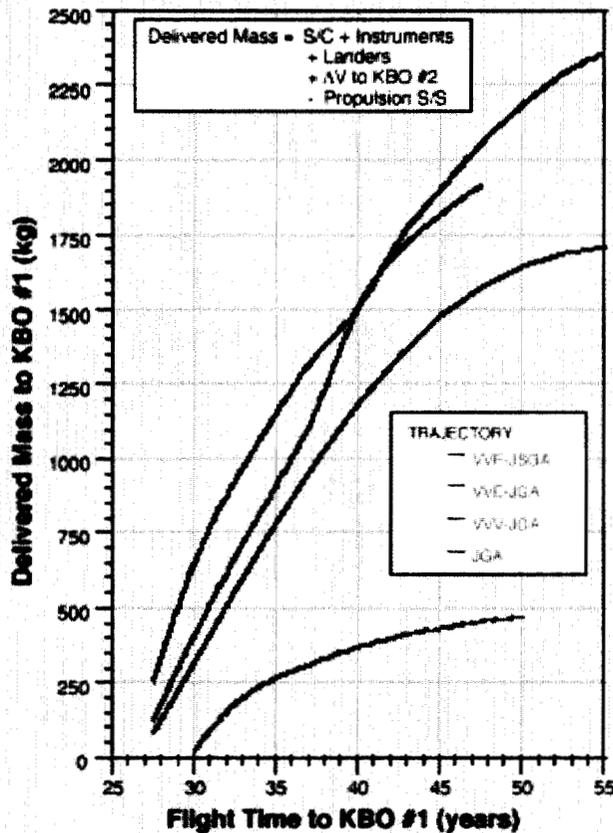


Figure 4. KBO Rendezvous Mission Chemical Trajectories.

The second alternative reviewed was the use of a very large solar concentrator to collect the power needed for an electric propulsion system. Both solar photovoltaic power conversion

systems (the usual approach to solar electric propulsion), and solar thermal power conversion systems (use static or dynamic thermal-to-electric power conversion system by replacing the nuclear reactor thermal energy with solar thermal energy) were considered. The greatest challenge is the development of 1-kilometer scale mirror/concentrator technology and, in the case of the photovoltaic option, the very large photovoltaic array.

The mirror/concentrator required for both implementations would have a concentration ratio (CR) of 1600 (at 40 AU compared to 1 AU) and a diameter of 800 - 900 m. It was assumed that at 100 kWe the power conversion efficiency would be between 20 and 25%. A low mirror areal density would be necessary for low overall system specific mass, yet a high/variable CR implies the need for good figure control – much more than for a solar sail of similar dimensions. These two requirements are in conflict; the specific mass of the projected mirror/concentrator was found to be too high to allow the desired spacecraft acceleration (i.e. trip time).

3.0 Conclusions and Future Plans

4.1 Propulsion Technology Advances Needed

For both the Interstellar Probe and Kuiper Belt Object Rendezvous missions, the high power levels, high efficiency, and long burn times required drive the need for new propulsion technologies. Solar sails and fission-powered electric propulsion systems seem the most promising propulsion technologies for this exciting exploration of near-interstellar space in the early part of the new millennium.

While there is now a substantial technology base in state-of-the-art kilowatt-level ion thrusters, new ion engine component technologies such as C-C (carbon-carbon) slotted grids were assumed in the interstellar precursor mission studies. C-C grids are required for long lifetime, while the assumed use of slotted grids comes from the need to reduce the beam divergence on one axis, and therefore reduce the beam impingement on other spacecraft components. Furthermore, additional graphite shielding, especially of the tanks, boom, and nuclear power system might be needed to reduce sputtering of external structures. The ion thruster design also requires a low flow neutralizer to improve total efficiency. A low discharge loss and a high discharge propellant efficiency will require an optimized design of the thruster magnetic circuit. Lifetime requirements are of concern especially with respect to the cathode erosion and cathode emitter degradation. High voltage propellant isolators will be required because of the high beam voltages.

The development of space nuclear reactors presents numerous challenges, both political and technical. Their use on deep space robotic probes will require significant collaborative efforts between NASA and the U.S. Department of Energy.

New carbon fiber materials for solar sails have been developed recently. These ultra low areal density, high temperature fabrics are very promising for close solar perihelion flyby trajectories. Also, thin, lightweight substrates are now available which can be qualified for space applications in near-term missions.

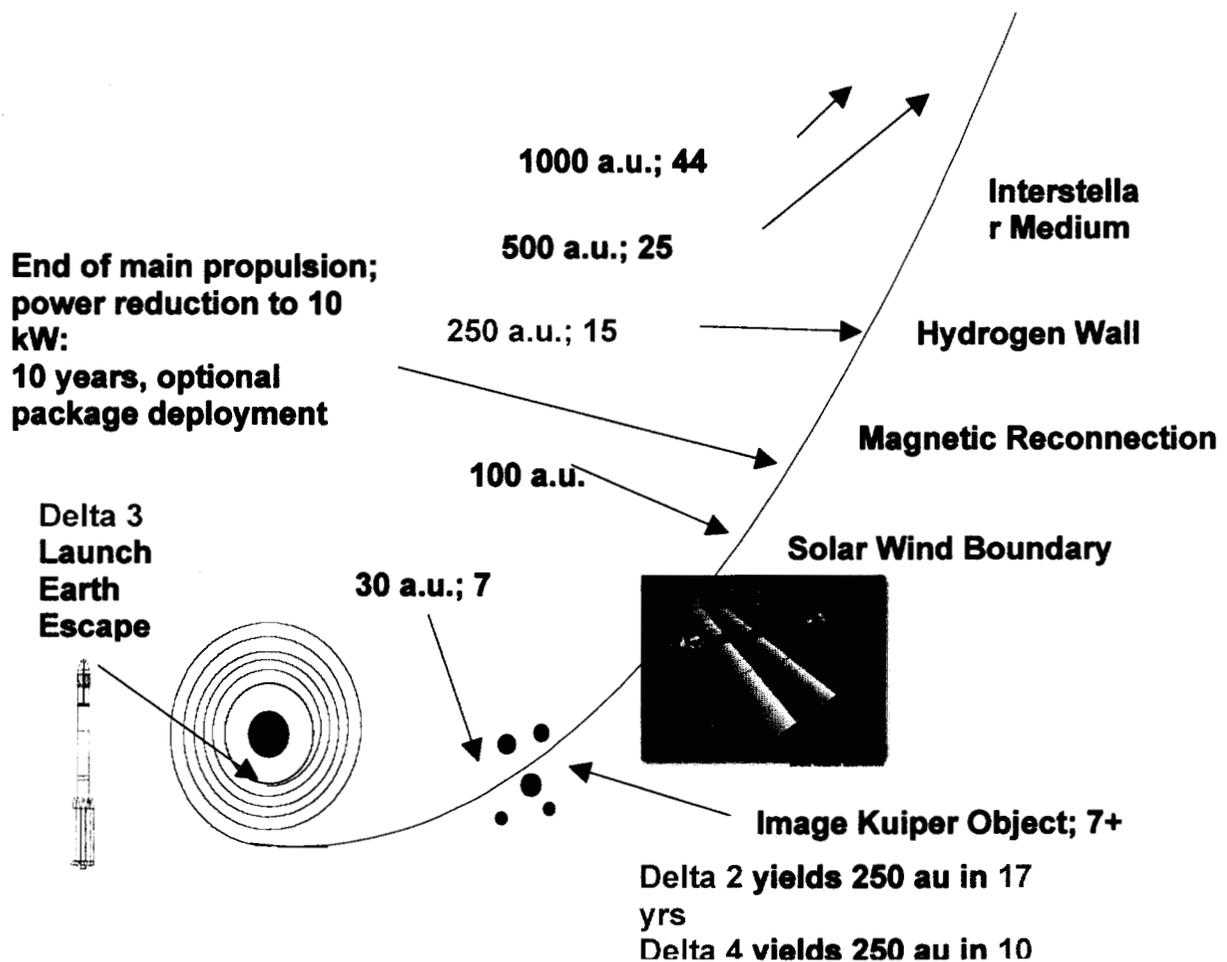
4.2 Beyond Interstellar Probe

The development of carbon fiber substrates with the thermal properties to survive close Solar perihelion maneuvers has the potential to dramatically alter our current view of interstellar exploration. Missions to 1000 AU and beyond can now be considered due to the high velocities achievable by solar sails via close solar swingbys. It has been calculated that a 1-km diameter sail using a 0.15 AU perihelion maneuver could reach 1000 AU within 21 years.^{viii} The missions that this capability may enable include the use of the sun as a gravity lens at 550 AU as well as exploration of the Oort Cloud.

Acknowledgements

The authors thank the members of the NASA Interstellar Probe Science and Technology Definition Team whose efforts resulted in the material for this paper. We also are appreciative of the contributions by Sandia National Laboratory on the Nuclear Electric Propulsion study, and to Team X – the JPL advanced system design team that examined the scenarios for both the Heliopause and Kuiper Belt Object missions.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and at the NASA Marshall Space Flight Center.



 NEP Power up upon C3=0

**THIS TRAJECTORY SHOULD
HAVE BEEN REDRAWN SEVERAL WEEKS AGO**

Figure 3. Notional trajectory for the Interstellar Probe using nuclear electric propulsion.

References

-
- ⁱ Garner, C. E. et. al., "A Summary of Solar Sail Technology Developments and Proposed Demonstration Missions," AIAA-99-2697, 35th AIAA Joint Propulsion Conference, June 20-24, 1999.
- ⁱⁱ Voyager Mission Operations Status Report #1074, May 29 Through June 4, 1999, NASA JPL.
- ⁱⁱⁱ Interstellar Probe Science and Technology Definition Team Meeting #1, Feb. 15-17, 1999 and Meeting #2, March 29-31, 1999, NASA JPL Report.
- ^{iv} E. J. Cutting, "Review of G. Vulpetti 'Momentum Reversal' Solar Escape Trajectories", JPL Internal Memorandum, April 12, 1999.
- ^v Garner, C. E. et. al., "A Summary of Solar Sail Technology Developments and Proposed Demonstration Missions," AIAA-99-2697, 35th AIAA Joint Propulsion Conference, June 20-24, 1999.
- ^{vi} R. A. Mewaldt, J. Kangas, S.J. Kerridge, and M. Neugebauer, "A Small Interstellar Probe to the Heliospheric Boundary and Interstellar Space", *Acta Astronautica* 35: pp 267-276, 1995.
- ^{vii} J.E. Randolph, A.D. McRonald, and M.J. Lewis, "Aero-gravity assist: fast interplanetary travel - a summary" Proceedings of the Workshop on Aeroassist Technologies, Jet Propulsion Laboratory, Pasadena, CA, Jan 14-16, 1997.
- ^{viii} Matloff, G. L., "Analysis of Several Candidate Interstellar Propulsion Systems," NASA Technical Report, MSFC, 1999.
- Vulpetti, G. "General 3D H-reversal trajectories for high-speed sailcraft", *Acta Astronautica*, 44: (1) pp 67-73, 1999, and "Sailcraft at high speed by orbital angular momentum reversal", *Acta Astronautica*, 40: (10) pp 733-758, 1997.

William Nesmith, Personal Communication, Jet Propulsion Laboratory, Pasadena, CA, July 1999.