# Analysis of Interstellar Probe Components for a Mission to an Earth-Like Planet

The 2007 NASA Academy
at Glenn Research Center:

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# 1 INTRODUCTION

On April 24, 2007, Stéphane Udry in Switzerland discovered the smallest known planet outside Earth's solar system to lie within its star's "habitable zone," where the conditions are right for liquid water. It was Gliese 581 c, the third planet out from the star Gliese 581 in the Libra constellation, 20.4 light years away. The planet is about five times Earth's mass—plenty of gravity to hold onto an atmosphere, but not enough to be a gas giant. Its age appears to be similar to Earth's, between 4 and 5 billion years.

Although Gliese 581 c is currently the most likely location for extraterrestrial life among the known planets, what astronomers can learn about it from its star's gravity-induced gyrations and spectral analysis is limited. To determine whether the planet has liquid water and whether life did exist, does exist, or could come to exist on the planet would require a less remote form of examination.

The 2007 Glenn NASA Academy proposes the development of a probe mission to an interstellar earth-like planet such as Gliese 581c, and has investigated potential technologies and mission designs for this purpose. The results of this investigation are presented here, concluding with suggestions of the types of research and technology NASA should pursue to make this or any other interstellar probe mission possible.

# 2 PROJECT OBJECTIVES

1. Provide detailed and useful descriptions and evaluations of key technologies and other design elements that could be used for an interstellar probe to Gliese 581 c.

2. Analyze implications of extraterrestrial exploration for space policy.

3. Compare competing design options to each other in an objective way.

4. Identify an optimum mission design and approach to the space policy associated with the mission.

5. Suggest areas where NASA should focus its research and technology development if it chooses to pursue an interstellar probe mission.

# 3 QUANTITATIVE TRADE ANALYSIS (QTA) EXPLANATION

Since many of the technologies considered for the probe mission do not have a long history of use, it was necessary to quantify each technology's potential usefulness and practicality in a way that depended as little as possible on the person doing the evaluation.

The solution used here is a Quantitative Trade Analysis (QTA), with a specialized rubric for each of four aspects of the probe mission: propulsion, power, autonomous systems, and scientific missions.

## *3.1 QTA Setup*

1. Each rubric is a series of scales on which a given technology option can be ranked, from one to five with five as the best.

2. The numbers on each scale are clearly defined, with numeric or otherwise objective criteria wherever possible.

3. The result of the QTA is a numerical score for each technology, so that different options scored by the same rubric (say, power systems) can be compared to each other.

4. Each scale within a rubric has a certain weight that reflects its importance and determines how much effect that scale has on the total score given by that rubric.

# 4 Scientific Missions

## *4.1 Introduction*

The scientific goals of this mission are fourfold. The main objective is to study the planet in detail and asses its habitability, determining what level of life it is capable of supporting and searching for any forms of life already present. A range of basic data will be collected about the planet and the surface will be mapped to the extent that possible landing sites can be identified. In addition, the area that the planet occupies, its star and any neighboring bodies will be studied.

If forms of life are found on an alien planet, then it is obviously capable of supporting life. However, if a large biosphere is not present, detecting the life forms is not necessarily simple. The first signs that life might be present are an atmosphere a magnetic field, and surface water. The maximum temperature on the planet is another important variable and depends largely on the distance of the planet from the star it orbits. Unsteady chemical reactions are generally a signal that life forces are at work and would be one of the first clues . These signals may be detected through a spectral analysis of the atmosphere and surface.

## *4.2 Science Goals*

Five main scientific goals were identified by the Scientific Missions team, and it was decided that each instrument would be evaluated on the spectrum of science that it contributes to on the mission. The ability to detect or refine the physical characteristics of the planet listed in Table 1 consisted of one main goal of the mission.

**Table 1. Primary desired planetary characteristics.**[12]

| |
|---|
| **Mean distance from Sun** |
| **Orbital period (sidereal)** |
| **Orbital eccentricity** |
| **Orbital inclination** |
| **Equatorial diameter** |
| **Mass** |
| **Mean density** |
| **Gravity** |
| **Escape speed** |
| **Rotation period** |
| **Solar day** |
| **Oblateness** |
| **Inclination of equator** |
| **Albedo** |
| **Surface atmospheric pressure** |

Another science goal is the ability to remotely detect the presence of life on the planet. This is most readily done if the planet has a significant atmosphere which is then analyzed for composition. If there are molecules present in considerable amounts that should have long since decomposed of their own accord (for example: oxygen and methane) then there is evidence that some other mechanism is replenishing the compounds. Such a detection scheme might offer evidence of substantial life, be it

developed or microbial. To identify the presence of more developed organisms would require the ability to sense signals, or large scale artificial planetary anomalies and structures greater than 100m.

It was deemed useful to determine whether or not a planet appears capable of developing or supporting life based on the environment of its surface. Some of the factors that feed into this assessment include the presence of a substantial magnetic field able to protect the planet from harmful radiation, the presence of a sizeable atmosphere, temperatures within a habitable region, composition including elements and compounds necessary for life, and the presence of water.

Imaging the planet and its star are of high priority for outreach in order to promote further exploration of interstellar systems.

## *4.3 Reference Missions*

### 4.3.1 Cassini-Huygens

**Figure 1: Cassini-Huygens Spacecraft Design.**[41]

**Cassini Orbiter science instruments: composite infrared spectrometer, imaging system, ultraviolet imaging spectrograph, visual and infrared mapping spectrometer, imaging radar, radio science, plasma spectrometer, cosmic dust analyzer, ion and neutral mass spectrometer, magnetometer, magnetospheric imaging instrument, radio and plasma wave science; Huygens probe science instruments: aerosol collector pyrolyser, descent imager and spectral radiometer, Doppler wind experiment, gas chromatograph and mass spectrometer, atmospheric structure instrument, surface science package.**[46]

There have been four spacecraft sent to investigate Saturn, but the Cassini spacecraft was the first to explore the rings and moons of Saturn from orbit. It was launched in 1997 and after four gravity-assists it entered orbit in July of 2004, where without delay it began sending images and data back to Earth. It will complete more than 70 orbits around Saturn and its moons. The European Space Agency's Huygens Probe entered Titan's atmosphere in January of 2005. Both spacecraft are providing scientists with valuable and intriguing data in order to help them better understand this region of the solar system. The Cassini orbiter and Huygens probe are equipped with numerous instruments so that they are able to obtain various measurements for their analysis. The main scientific goals include measuring Saturn's very large magnetosphere, analyzing the rings from a closer perspective and studying Saturn's composition and atmosphere.[46]

Cassini has the ability to map Titan, Saturn's largest moon, using a cloud penetrating imaging system, which is difficult due to Titan's very thick atmosphere. The instruments on the Huygens probe allowed for detailed analysis of the chemical composition of Titan's atmosphere and of the surrounding clouds. The probe landed on Titan's equator approximately two hours and twenty-seven minutes after entering the atmosphere. It survived impacting the frozen surface and was able to communicate data with the Cassini spacecraft for a few minutes. Huygens is currently the furthest

human-made object ever to land on a celestial body[46].

The instruments selected for further research include the Ultraviolet Imaging Spectrograph (UVIS), the Ion and Neutral Mass Spectrometer (INMS) and the Radio Science Subsytem (RSS).

**Table 2: Cassini-Huygens at a Glance.[46]**

| Cost | Mass | Power |
|---|---|---|
| $3.27 billion | 1 million kg | 633 W |

### 4.3.2 Messenger

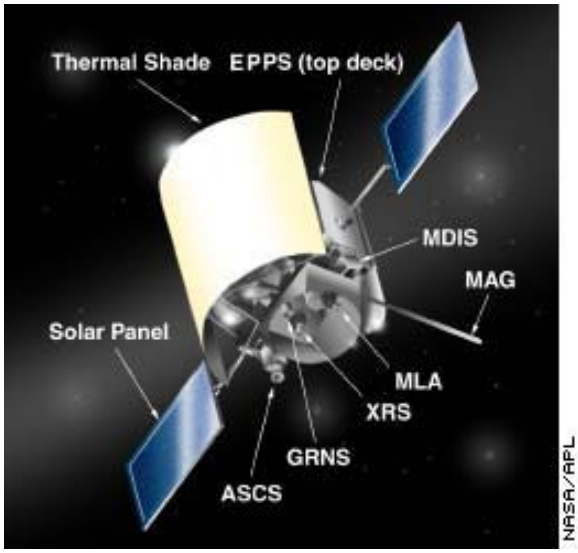


**Figure 2. Artist representation of the MESSENGER probe. (reference: www.astronomytoday.com)**

**Mercury Dual Imaging System (MDIS): a camera with wide and narrow fields-of-view, for monochrome, color and stereo imaging. Gamma-Ray and Neutron Spectrometer (GRNS): which maps the elemental makeup of Mercury's crust. X-Ray Spectrometer (XRS): also used to map elemental abundances in crustal materials. Magnetometer (MAG): which maps the detailed structure and dynamics of Mercury's magnetic field and searches for regions of magnetized crustal rocks. Mercury Laser Altimeter (MLA): which measures the planet's topography. Mercury Atmospheric and Surface Composition Spectrometer (MASCS): which measures the abundance of atmospheric gases and detects minerals in surface materials. Energetic Particle and Plasma Spectrometer (EPPS): which measures the makeup and characteristics of charged particles within and around Mercury's magnetosphere.**

MESSENGER launched August 3, 2004 and headed toward Mercury. The goal is to study Mercury in depth: determine its geologic history, determine the characteristics of the core, study its magnetic field, identify surface materials, and determine the reason for the planets high density. Scheduled time of first data collection.

MESSENGER was selected as a reference mission because many of its scientific instruments are designed specifically to study terrestrial planets. The specific instruments which are covered in this report are the GRNS, XRS, MAG, MLA, MASCS, and EPPS.

**Table 3: MESSENGER at a Glance**

| Cost | Mass | Power |
|---|---|---|
| $286 million | 1093 kg | 640 W |

### 4.3.3 New Horizons

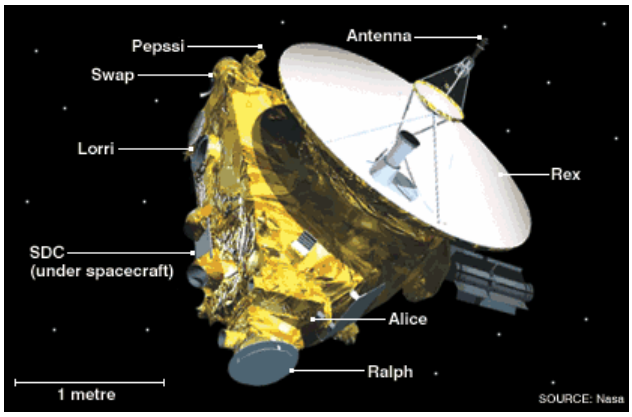


**Figure 3. New Horizons Instrument Suite.**

**PEPSSI: Measures particles escaping from Pluto's atmosphere; SWAP: Measures interaction of Pluto with solar wind; LORRI: Powerful telescope and digital camera fortified against cold; SDC: Detects dust grains from collisions in Kuiper Belt; RALPH: Makes maps of Pluto, moons and Kuiper Belt Objects; ALICE: Probes composition and structure of Pluto's atmosphere; REX: Measures atmospheric pressure and temperature.**[12]

The New Horizons spacecraft launched into flight as the payload of an Atlas V rocket on January 19, 2006. Its list of targets for scientific measurement and observation include close encounters with Pluto, its moons Charon, Nix, and Hydra, as well potentially some other objects of the Kuiper belt. New Horizons is one of NASA's New Frontiers missions targeting planetary exploration and is scheduled to begin data collection of Pluto in 2015.[55]

The instrument suite aboard the craft include several imagers of varying spectral sensitivities, solar wind and energetic particle analyzers, the Student Dust Counter, and atmosphere characterizing remote sensors. Several of these instruments appeared to be readily applicable to interplanetary exploration, especially to collect and refine data essential to the design of return missions. The instruments selected for further research include both of the imagers associated with RALPH: MVIC and LEISA, LORRI, and SWAP.

**Table 4. New Horizons Mission At a Glance.**[9]

| Cost | Mass | Power | Max Velocity |
|---|---|---|---|
| $650 million | 478 kg | 200 W | 27 km/s |

This particular mission design is a first step toward interstellar exploration as it optimizes several essential qualities characteristic of long term, high speed operations. Low mass design specification allows the craft to reach speeds faster than 25 km/s after gravity assisted acceleration from Jupiter. Mass and power conservation are essential elements to increasing the operational lifetime of a mission. The craft also was designed to occupy more space than absolutely necessary in order to provide radiation shielding for its internal components from the Radioisotope Thermoelectric Generator (RTG) power source.[3]

Several of the probe's instrument packages were also designed specifically with longevity in mind and include insulated "doors" that protect the sensors from micrometeoroids, contamination, and harmful solar illumination. The many design characteristics that make New Horizons able to perform its mission past the edge of the solar system are directly applicable to interstellar exploration, hence the reason for further study of this particular system.

## *4.4 Scientific Instruments*

### 4.4.1 Energetic Particle Spectrometer (EPS)

**Figure 4: New Horizons EPS module.**

**Energetic Particle Spectrometer (EPS)-Missions: New Horizons**

Energetic Particle Spectrometers are able to detect an array of different particles traveling through space. They are used to study atmospheric escape rates and the paths and compositions of magnetic fields around planets and on a system wide level. Currently, these instruments are employed in the inner and outer heliosphere and earth's orbit. An EPS works by measuring the velocity, total energy, and angle of arrival of a particle. From this data, the type and trajectory of the particle can be determined.

In general, the sensing portion of an EPS is made up of two parts, a Time-of-Flight (ToF) telescope which measures the velocity and angle of arrival of the particle, and a Solid State Detector which primarily detects electrons. Each sensor on an EPS is accompanied by a Signal Conditioning Unit which amplifies signals, separates particle events and serves as an interface between the sensing and processing units. Digital Processing Unit.

Can provide information about the temperature of the outer atmosphere, the mass of the planet, how the atmosphere and planet are evolving. Will provide information about particle density and movement between solar systems.[22]

### 4.4.2 Magnetomoter

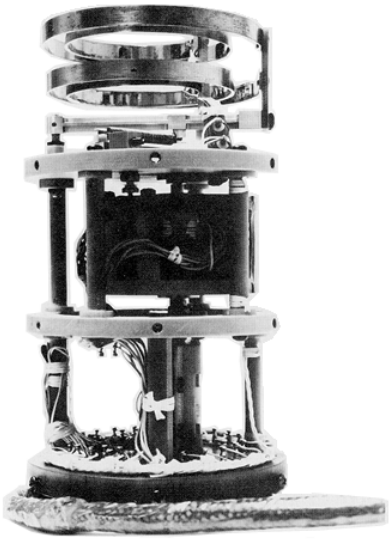

**Figure 5. Galileo Magnetometer.**

Magnetometers are used to characterize magnetic fields. Depending on the type and set-up, they are capable of determining both the strength and direction of external magnetic fields in the vicinity of the instrument. The two basic types used on satellites and space probes are the triaxial fluxgate magnetometer and the vector helium magnetometer. The former has three sensors arranged orthogonally which measure the component of the field along their respective axes. The flux gate detects external magnetic fields by producing its own field and measuring any disturbances in that field. In contrast, the vector helium magnetometer measures the field by first

producing voltages along three axis which cancel out the voltages produced by the external field. The helium magnetometer requires that metastable helium be produced on the probe and pumped through the instrument.

Knowing the presence and strength of a planet's magnetic field is an important factor when considering the planet's habitability. Beyond that it can be used to help determine the composition of the core of the planet.

Sources: THE GALILEO MAGNETIC FIELD INVESTIGATION

### 4.4.3 Radio Plasma Wave Detector

**Reference Mission: New Horizons**

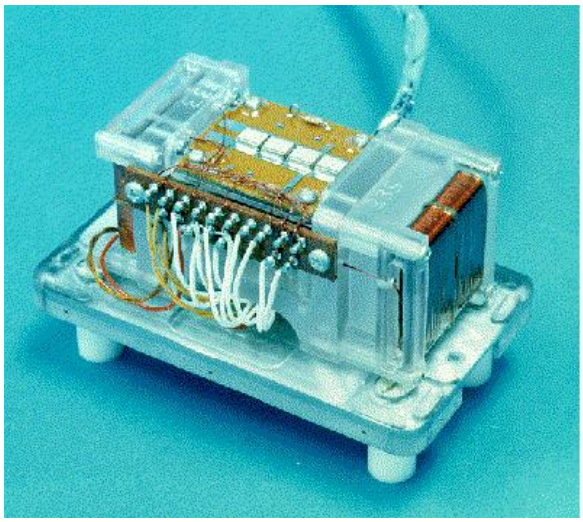

**Figure 6. Radio Plasma Wave Detector.**

Plasma waves have long been believed to play an important role in solar wind dynamics. Plasma wave studies have been carried out throughout the solar system, generally focusing on the interactions between the earth and sun and within the vicinity of Jupiter's magnetic field. The basic purpose of plasma wave detectors is to study the characteristics of plasma waves both in interplanetary space and within range of the effects of planetary and stellar magnetic fields. This is done by measuring electric fields, magnetic fields, electron density and temperature.

For thorough analysis of plasma waves, an instrument package requires both electric and magnetic field antennas capable of measuring components of both fields along three axis. Also necessary for the collection of electron density is a Langmuir probe, which electron temperature and density and plasma potential.

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### 4.4.4 Radio Science Subsystem

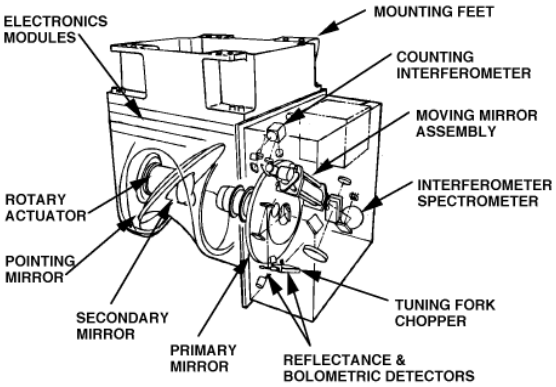


**Figure 7. Radio Science Subsystem.**

A Radio Science Subsystems is a very common instrument for probes deployed anywhere in the solar system. Its uses are as varied as the destinations. An RSS uses Doppler shift to determine the strength of gravitation fields which can be used to determine the mass of the body producing field. Atmospheric, ionospheric and planetary ring occultation measurements are also possible with an RSS. Analyze plasma content, solar wind, relativistic effects of the sun and gas giants on radio waves. Provides tracking and trajectory data

Generally operates across two or three frequency bands, S-, X-, and Ka-bands. Having multiple frequency bands is important for analyzing any plasma effects since the different bands are either more or less susceptible to perturbations caused by the plasma. Comparing Doppler and phase shifts between the bands provides information on the density, composition and velocity of the plasma waves.

A limiting factor for use of an RSS on an interstellar mission will be that most of the data is collected on earth and provides details about the materials which the waves have passed through between the probe and collecting dish.

### 4.4.5 Dust Counter

A dust counter is a very self-explanatory instrument. It collects and counts particles as it passes through space. These particles do not necessarily have to be dust, just dust sized. It is possible to determine the mass, composition and velocity of the particles if an impact-ionization counter is used.

A dust counter would be useful on an interstellar mission not only anytime during the journey but also after reaching its destination.

### 4.4.6 Ion and Neutral Mass Spectrometer (INMS)

#### Reference Mission: Cassini-Huygens

The purpose of this instrument is to study the chemical, elemental and structural composition of gaseous and volatile components of neutral particles and low energy ions in the planet's atmosphere, and if applicable, the ionosphere and magnetosphere.[47]

The INMS will study atmospheric chemistry and the possible interaction between layers of atmosphere, if they exist. It will measure ion and neutral species composition and structure of the atmosphere[47] above 950 km. The remote sensing instruments included with INMS include cameras, spectrometers, radio and radio sensors.[34]

In-situ direct sensing measurements around the spacecraft will be performed using fields and particles instruments so as to measure possible magnetic fields, neutral and charged particle composition, the composition of dust particles and the properties of plasma waves. It has a sensor equipped with a quadruple mass spectrometer designed to measure in-situ low-density gas and positive ions in the planetary upper atmospheres without any pressure reduction (see Fig. 2).[34]

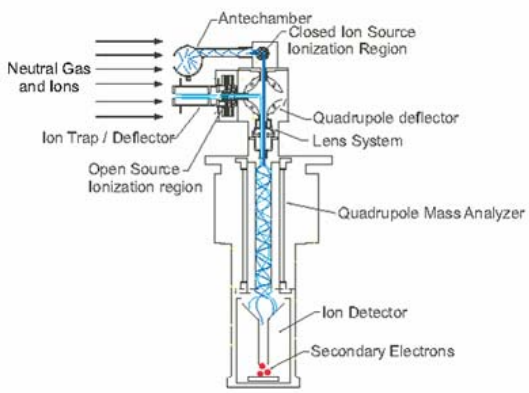


**Figure 8: Ion Neutral Mass Spectrometer[35].**

The mass of the instrument is 9.25 kg with a 1.4 kg tantalum radiation shield that is 0.23 cm thick. While in neutral mode, INMS runs on 23.3 W power, on average. While in ion mode it is running on 20.9 W and 13.1 W while in sleep mode.[34,18]

The telemetry rate for INMS will be 1498 bps, with a 31.1 ms integration period and a 34.0 ms total sample period.[34,18] This instruments has an ion flux sensor sensitivity of $10^{-3}$ (counts/sec)/(ions/cm$^2$/sec) with a maximum energy of approximately 100 eV. It has a neutral mode sensor sensitivity of $2.5 \times 10^{-3}$ (counts/sec)/(particle/cm$^3$) (closed and open source). Its viewing angle for open source is approximately 8º cone half angle and approximately $2\pi$ steradians for both closed source and for exhaust vent (see also Fig. 3).[18]

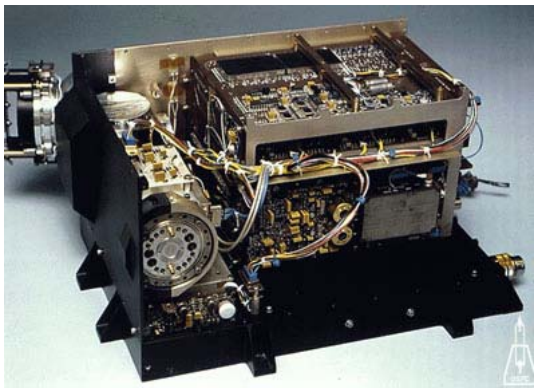

**Figure 9: The INMS Instrument on the Cassini Orbiter.[47]**

The dimensions of the INMS instrument are 20.3 cm (H) x 42.2 cm (L) x 36.5 cm (W).[34] Figure 3 shows the INMS instrument aboard the Cassini spacecraft.

### 4.4.7 Gamma Ray and Neutron Spectrometer (GRNS)

Reference Mission: MESSENGER

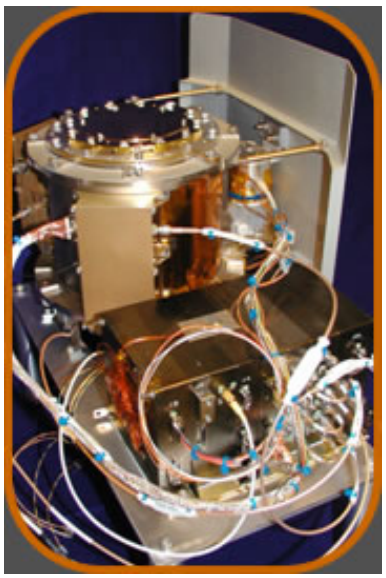

**Figure 10. The GRS Instrument on the MESSENGER Spacecraft.[43]**

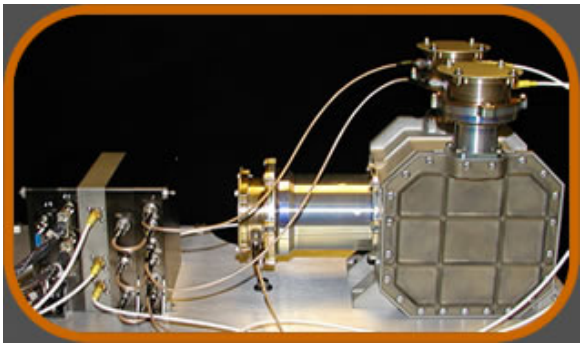

**Figure 11. Neutron Ray spectrometer.[43]**

The Gamma Ray and Neutron Spectrometer will determine the elemental abundances in the crust of the planet.[45] It can discern elements such as hydrogen, magnesium, silicon, oxygen, iron, titanium, sodium and calcium. GRNS will note the gamma ray fluorescence and thermal neutron emission from the planet's surface, if any.[12] The gamma rays that are emitted have uniquely identifiable signatures of energy, thus distinguishing which chemical element is

present in the possible soil and rock of the planet's surface. The GRNS instrument provides an energy resolution better than 8.0%.[12]

The instrument uses a γ-ray scintillator, which is mounted in a cup-shaped bismuth germinate active shield that is 1.25 cm thick, to measure elemental abundances. The primary GRS detector is a 50 x 50 mm cesium iodide (CsI) scintillator, which operates at near room temperature, thus is ideal for a long-duration mission since cryogenic cooling is not required and it is virtually immune to radiation damage.[12]

The neutron spectrometer has high enough sensitivity to locate possible $H_2O$ ice at the poles of the planet. The NS has two lithium glass scintillators separated by a borated-polymer block scintillator which can measure thermal, epithermal, and fast neutrons.[12]

**Table 5. GRNS Instrument Specifications.[45]**

| Mass | Peak Power |
|---|---|
| 13.1 kg | 23.6 W |

### 4.4.8 X-ray Spectrometer (XRS)

### Reference Mission: MESSENGER

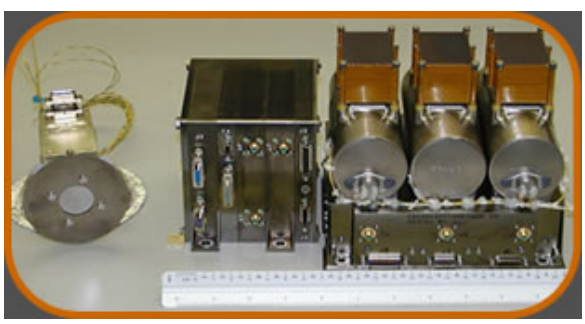

**Figure 12: The X-ray Spectrometer onboard MESSENGER.[48]**

The XRS is the perfect instrument to remote sense and determine the elements present, as well as their abundances, within the uppermost 1 mm of the surface of the planet.[48] It will use possible X-ray fluorescence from the surface of the planet due to solar X-ray emission to catalog elements such as magnesium, aluminum, silicon, sulfur, calcium, titanium and iron.[12] The data collected by the XRS will be formulated into a map of which elements are present and their locations. This instrument is integral to an interstellar mission in that it helps characterize the planet's chemical composition and geologic history.[48]

The XRS instrument includes three gas-filled detectors with which it views the planet and an Si-PIN detector to view the local star. Lower energy X-ray lines such as aluminum, magnesium and silicon are differentially separated by thin absorption filters located on two planet-facing detectors.[13]

Two of the three detectors provide spectral selectivity through filters; one solid-state detector pointing at the local star; and a beryllium-copper honeycomb collimator that provides a 12-degree FOV.[12]

The XRS gathers energy spectra from 1 to 10 keV, covering K-fluorescence emission lines of magnesium, aluminum, silicon, sulfur, calcium, titanium, and iron with an energy range of 0.7 to 10 keV and an energy resolution of 850 eV fwhm at 5.9 keV.[13]

**Table 6. XRS Instrument Specifications[45].**

| Mass | Peak Power |
|---|---|
| 3.4 kg | 11.4 W |

### 4.4.9 Laser Altimeter

**Reference Mission: MESSENGER**

**Figure 13 The Laser Altimeter Aboard MESSENGER Spacecraft.[48]**

The Laser Altimeter will be able to determine the topography of the planet under study. It can view the planet from up to 1,000 km and obtain surface profiles.[12,45] The LA can also determine surface altitude profiles with an accuracy of 30 cm from an altitude of 1,000 km as it strobes the surface of the planet with eight pulses per second delivered by its transmitter.[12] The transmitter aboard the LA is a Q-switched, diode-pumped Cf:Nd:YAG laser transmitter that operates at 1064 nm.[13]

The timing process initiates when the laser fires and a small fraction of the beam is sampled by optical fiber and relayed into a start detector.

The LA has a 4-lens refractive receiver telescope, which collects back-scattered laser echo pulses that are detected with a hybrid avalanche photodiode assembly.[13] The receiver on the LA has four sapphire lenses, a photon-counting detector, a time-interval unit and processing electronics. The electronics of the receiver can record arrival time of individually reflected photons with a 75 cm resolution.[45]

**Table 7. LA Instrument Specifications.[45]**

| Mass | Peak Power |
|---|---|
| 7.4 kg | 38.6 W |

### 4.4.10 Atmospheric and Surface Composition Spectrometer

**Reference Mission: MESSENGER**

**Figure 14: The Atmospheric and Surface Composition Spectrometer on the MESSENGER Spacecraft.[44]**

The purpose of the instrument is to measure the abundance of atmospheric gases and detect minerals in surface materials.[45] This type of an instrument is important for an interstellar mission. Once detection of an atmosphere around the planet is confirmed, the next scientific goal would be to determine its elemental composition and that of the surface of the planet.

The ASCS includes an ultraviolet spectrometer and infrared spectrograph. It will be used to observe trace atmospheric gases around the planet and map minerals in the planet's surface.[12]

The Ultraviolet-Visible Spectrometer (UVVS) measures the composition and spatial and temporal changes in exospheric species. This particular part of the instrument is optimized for measuring the composition and structure of surface reflectance. The Visible-Infrared Spectrograph (VIRS) maps surface reflection in order to determine the mineral composition in the surface.[12,36] The best resolution of the UVVS is 25 kilometers, while VIRS is 3 kilometers.[12]

**Table 8 ASCS Instrument Specifications.[42]**

| Mass | Peak Power |
|---|---|
| 3.1 kg | 8.2 W |

### 4.4.11 Ultraviolet Imaging Spectrograph (UVIS)

### Reference Mission: Cassini-Huygens

An ultraviolet imaging spectrograph has many potential uses on an interstellar planetary mission. Such an instrument possesses capabilities to capture high detail pictures and even video of planets, moons, and ring structures.

Through the detection of reflected UV light, ring structure, atmospheric composition and distribution, aerosol particle content, and atmospheric temperatures can all be measured.[9]

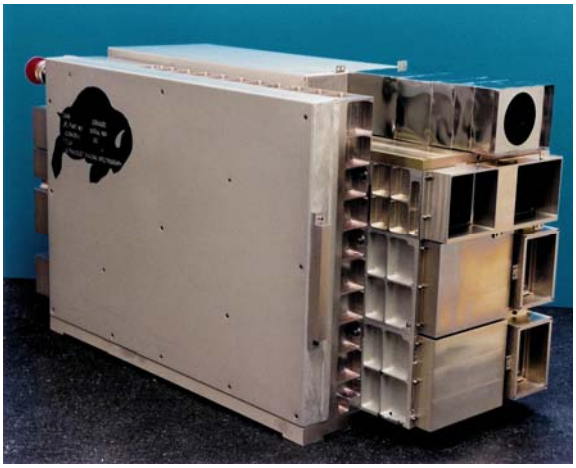

**Figure 15. UVIS Instrument.[54]**

These data provide for a detailed understanding of the atmospheric conditions of an interstellar planet, providing great insight into the planet's capability to support life and further human missions. Ultraviolet waves reflected from cloud cover and haze can be used to determine how closely the probe may be able to orbit the planet, an important feature for image resolution and instrument sensitivity, and because of its independence of the presence of visible light, some features of a celestial body can be imaged even under the near total darkness of its shadow.[9]

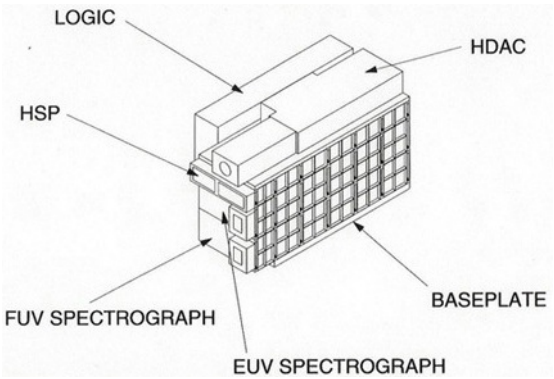


**Figure 16. UVIS Instrument Layout.[54]**

The instrument consists of multiple telescopes categorized by their spectrographic channels: extreme or far

ultraviolet (EUV and FUV respectively). EUV light is used to collect data that can be used to create false color images and analyze atmospheric composition, while FUV is also able to image rings.

A UVIS was used on the Cassini probe to detect atmospheric components including: hydrogen, oxygen, methane, water, acetylene, and ethane.[9] Additionally, the UVIS instrument possesses greater functionality via high-speed photometer, hydrogen-deuterium absorption cell, and electron multiplier channels. This allows it to also record the density of materials in rings and the levels of hydrogen and deuterium in the planetary system which may be particularly useful to record for in-situ fuel production.[53]

### 4.4.12 Multispectral Visible Imaging Camera (MVIC)

#### Reference Mission: New Horizons

The inclusion of a high resolution visible imaging instrument capable of providing surface composition data and detailed maps of surface features provides information critical to the decision making process for identifying landing sites of future missions, possibilities of in-situ resource utilization applications, and image analysis.

New Horizons makes use of a single telescope dubbed RALPH with two separate detectors as components of an imaging system.

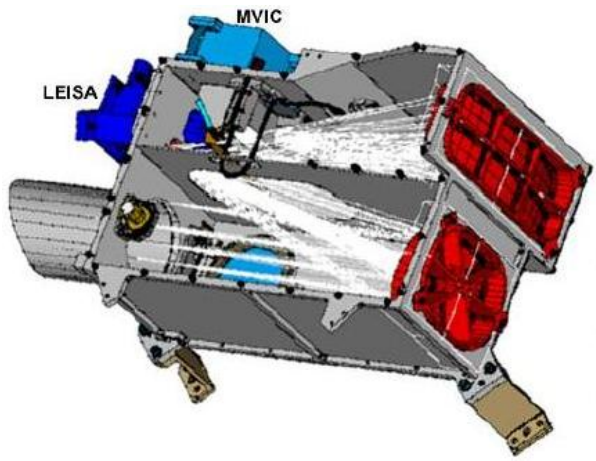


**Figure 17. RALPH Cutaway View.[53]**

The Multispectral Visible Imaging Camera (MVIC) is one portion of RALPH that remotely images a planet to create color and panchromatic maps, detects the presence of an atmosphere, checks for rings, and is able to identify the presence of orbiting satellites. Mapping a planets surface yields insight into various aspects of its history including cratering, scale of surface features, and types of structures existing on the surface.[53]

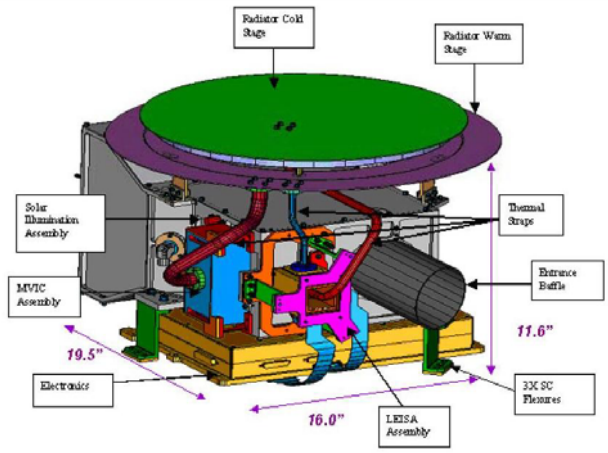


**Figure 18. RALPH Assembly.[53]**

**RALPH instrument and component locations are shown on this instrument rendition.**

MVIC will provide hemispheric panchromatic and 4-color maps at spatial

resolutions less than 10 km. The MVIC consists of seven CCD arrays which when operate in smaller groups to map features in blue (400-550 nm), red (540-700 nm), near IR (780 – 975 nm) and narrow band methane (860 – 910 nm) wavelengths.[53]

### 4.4.13 Linear Etalon Imaging Spectral Array (LEISA): Infrared Spectrometer

**Reference Mission: New Horizons**

Infrared spectrometers could be used to read thermal signatures emitted or reflected from the surface of celestial bodies. This particular instrument, LEISA, is the second of two detectors that comprise New Horizons' RALPH remote sensing instrument package. Linear etalon imaging employs a prism-like component (the etalon) to separate different wavelengths of light, allowing them to be analyzed independently.[3]

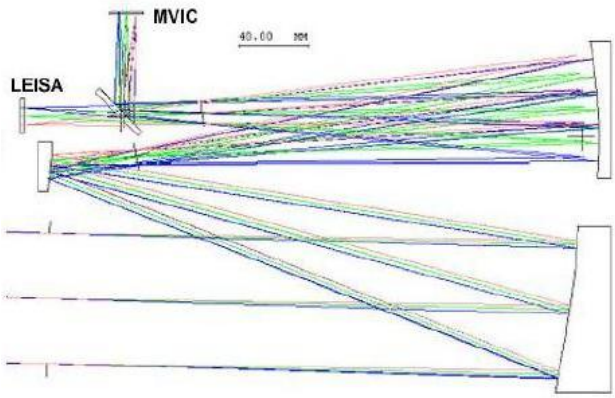


**Figure 19. RALPH Ray Diagram.** [3]

LEISA's capabilities include hemispheric near-infrared spectral mapping at resolutions exceeding 10 km/pixel, surface temperature mapping, phase-angle dependent spectral maps, phase-angle-dependent spectral mapping, and hemispheric distributions of $N_2$, CO, and $CH_4$ at a resolving power of approximately 250.[55] A higher resolution component capable of achieving a resolving power of near 560 can image surface mixing states, phase composition, and differentiate between grain sizes.[55] LEISA's mapping capabilities will help identify molecular surface distribution, the presence of frost, and the effects of seasonal transport on surface distribution.[53]

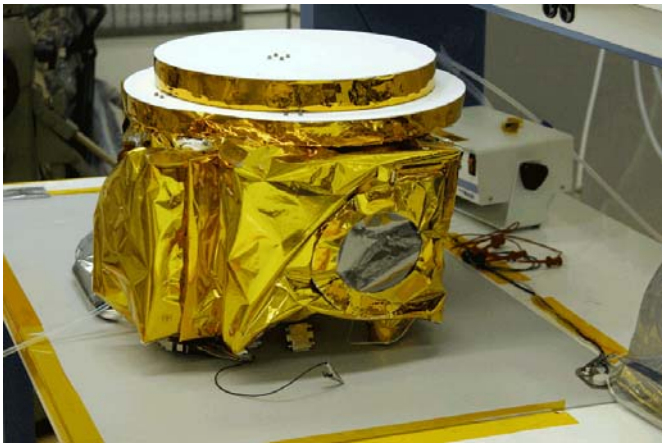

**Figure 20. RALPH Assembled.**[52]

### 4.4.14 Long Range Reconnaissance Imager (LORRI)

**Reference Mission: New Horizons**

The Long Range Reconnaissance Imager aboard the New Horizons space probe is a high resolution visible light CCD imaging telescope. This instrument is capable of discerning features as small as 100m and would provide visual spectrum images of a planet's geology, surface morphology, collisional history, and atmospheric interactions.[3]

**Figure 21. LORRI Assembled.[3]**

An imager such as LORRI is particularly well suited to high velocity short duration encounters with celestial objects, an important design aspect if an interstellar probe is unable to slow enough to enter planetary orbit. LORRI's capabilities lie mostly with visual spectrum mapping: hemispheric panchromatic maps, high resolution panchromatic maps of the terminator region, and panchromatic wide phase angle coverage of the planet. Further capabilities include searching for atmospheric haze, satellites, and rings as well as establishing the planet's radius, mass, density, and orbit.[3]

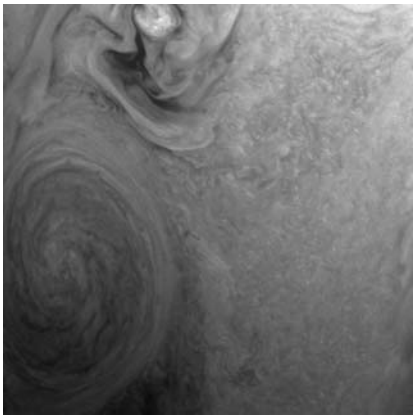

**Figure 22. Little Red Spot near limb as seen by LORRI at 3.0M km range.[3]**

LORRI maintains the ability to image characteristics monochromatically under low light conditions and also serves to help aid in determining trajectory corrections through navigational imaging.

This particular instrument is well suited for missions requiring significant longevity as it employs the use of a door that protects the instrument from intense light and contamination for the majority of its flight. The door opens (one time only) as the probe comes within range of its first target to be imaged. This could be modified as needed to reseal, or to only open upon arrival at the destination.

### 4.4.15 Solar Wing Around Pluto (SWAP) Solar Wind Analyzer

**Reference Mission: New Horizons**

The SWAP instrument aboard New Horizons functions in the observation and characterization of the solar wind and its interactions with the planet. Specifically it is able to discern the rate of atmospheric escape from the surface of a planet. Atmospheric escape occurs much more significantly on planets lacking magnetic fields can be described by taking data on the solar wind's velocity, density, and energetic particle flux.[12]

**Figure 23. SWAP on New Horizons.[8]**

SWAP is also able to characterize the energetic particle environment around a planet which may be significantly different from our own depending on the type of star at the center of the planet's orbit. An instrument such as this is also able to indirectly detect the presence of magnetic fields.

This particular design for a solar wind analyzing instrument was based on several requirements of the New Horizons craft that are directly relevant to an interstellar probe mission. SWAP is extremely efficient in its mass and power consumption and possesses high sensitivity, as it was designed to detect the solar wind interactions with Pluto from 30 AU away.

## *4.5 Scientific Missions QTA*

Each instrument selected for applicability to an interstellar mission was then evaluated against several criteria in order to determine its contribution to an interstellar probe mission. The fifteen instruments were given scores in three different categories: Mass, Power, and the number of Scientific Goals to which it could be applied on a standard 1 to 5 scale.

The mass scores were evaluated on a comparative level based on the maximum and minimum values observed among the fifteen instruments. The instruments were relatively evenly distributed across a range of 0.0 to 12.0 kg with 3.0 kg intervals and fit a linear correlation with reasonable accuracy. It was because of this fit that the QTA score ranges were decided to be evenly incremented. Fig. 11 portrays the linear correlation as formed by the instrument masses which fits with reasonable $R^2$ value of 0.9676.

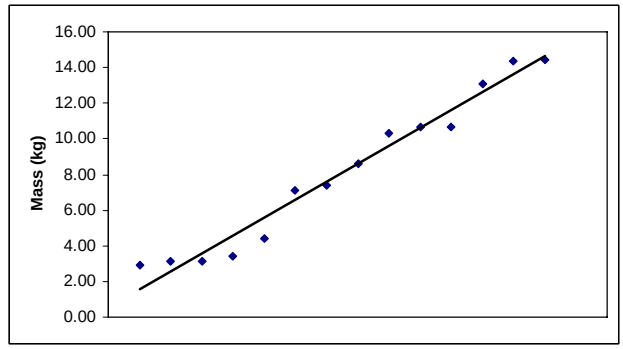


**Figure 24. Linear Correlation of Instrument Mass.**

Power posed a different problem since the data covered a much higher range of values and did not linearly correlate to a strong degree. The fit was found to be better suited to a natural log scale with a moderate $R^2$ value of 0.9292.

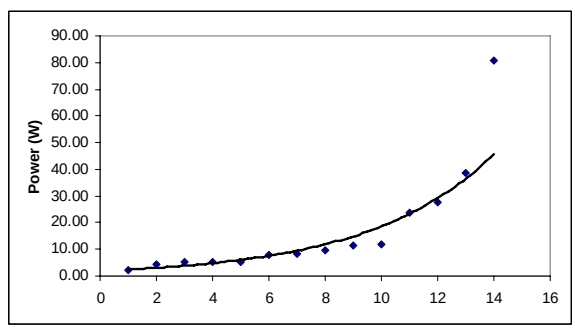


**Figure 25. Natural Logarithmic Correlation of Instrument Peak Power.**

The natural log of the peak power for each instrument was used to determine the ranges for the QTA values.

Scientific mission QTA scores were evaluated based on the number of science goals that the instruments were able to contribute towards. Each goal was weighted to have the same importance as any other, and so the number of goals an instrument can be applied to is equal to its QTA score for its section.

The QTA rubric displayed below in Table 9 was used to evaluate each instrument individually in order to compare their applicability to an interstellar mission.

**Table 9. QTA Scoring Rubric.**

| QTA SCORE | MASS RANGE | LN(POWER) RANGE | GOALS MET |
|---|---|---|---|
| 1 | 12.0+ | 4.0+ | 1 |
| 2 | 9.0-12.0 | 3.0-4.0 | 2 |
| 3 | 6.0-9.0 | 2.0-3.0 | 3 |
| 4 | 3.0-6.0 | 1.0-2.0 | 4 |
| 5 | 0.0-3.0 | 0.0-1.0 | 5 |

**The QTA score awarded to an instrument in each category lies on a 1 to 5 scale, with 5 being the best and 1 being the worst score possible. Scientific goals were not deemed to be equal in significance to the mission when compared against mass or power requirements. Their scores were weighted by multiplying their number of goals met by a factor of 4, making science goals twice as important as the mass and power requirements combined. The total score was then normalized to a 1 to 5 scale, the standard QTA comparison scale for the purposes of this report. A complete table of masses, peak power requirements, and scientific goals achievable are listed in Table 10.**

**Table 10. QTA Instrument Scoring**

| QTA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Instrument** | **Mass (kg)** | **QTA Score** | **Power Required (W)** | **QTA Score** | **Science Goals** | **QTA Score** | **QTA Total** |
| Ultraviolet Imaging Spectrograph (UVIS) | 14.46 | 1 | 11.83 | 3 | 1,2,3,4 | 4 | 3.33 |
| Multispectral Visible Imaging Camera (MVIC) | 10.67 | 2 | 5.30 | 4 | 1,3 | 2 | 2.33 |
| Linear Etalon Imaging Spectral Array (LEISA) | 10.67 | 2 | 5.30 | 4 | 2,3 | 2 | 2.33 |
| Long Range Reconnaissance Imager (LORRI) | 8.59 | 3 | 5.10 | 4 | 1,2,4 | 3 | 3.17 |
| Solar Wind Around Pluto (SWAP) | 2.94 | 5 | 2.25 | 5 | 1,3,5 | 3 | 3.67 |
| Energetic Particle Spectrometer | 3.10 | 4 | 7.80 | 3 | 1,3 | 3 | 3.17 |
| Dust Counter | 1.60 | 5 | 5.10 | 4 | 3 | 2 | 2.83 |
| Magnetometer | 4.40 | 4 | 4.20 | 4 | 3 | 1 | 2.00 |
| Radio Plasma Wave Subsystem | 7.10 | 3 | 9.80 | 3 | 5 | 1 | 1.67 |
| Radio Science Subsystem | 14.38 | 1 | 80.70 | 1 | 1,3,4,5 | 4 | 3.00 |
| Ion and Neutral Mass Spectrometer (INMS) | 10.29 | 2 | 27.70 | 2 | 2,3 | 2 | 2.00 |
| Gamma Ray and Neutron Spectrometer | 13.10 | 1 | 23.60 | 2 | 2,3 | 2 | 1.83 |
| X-ray Spectrometer | 3.40 | 4 | 11.40 | 3 | 3,5 | 2 | 2.50 |
| Laser Altimeter | 7.40 | 3 | 38.60 | 2 | 1,3 | 2 | 2.17 |
| Atmospheric and Surface Composition Spectrometer | 3.10 | 4 | 8.20 | 3 | 2,3,5 | 3 | 3.17 |

**Table 11 Science Goals**

| | | |
|---|---|---|
| 1 | Physical characteristics | See Table 1. |
| 2 | Detect life already present | Unsteady chemistry, artificial radiation (light, signals, waves), artificial structures |
| 3 | Detect characteristic of a habitable planet | Strong magnetic field, atmosphere, temperature, composition, water |
| 4 | Imager | Mapping, topography |
| 5 | study alien sun | Characteristics, imaging, solar wind |

# 5 Propulsion Systems

## *5.1 Chemical*

Chemical rockets use the heat of combustion of the fuel to heat and accelerate the gaseous products of the rocket through a nozzle, accelerating the rocket in the opposite direction by Newton's Second Law.

### 5.1.1 Radioisotopes QTA Evaluation (see Appendix 11.1)

ISP: 1
Mass: 3
Reliability: 5
Cost to develop: 5
Cost to implement: 4
Time to develop: 5
Mission Time: 1
Safety: 4
*Total*: 3.39

### 5.1.2 Discussion

Liquid-fuel rockets that burn hydrogen and oxygen are currently the most fuel-efficient type of chemical propulsion. Nonetheless, in terms of specific impulse, they are far from ideal for interstellar missions. The space shuttle main engines have an Isp around 450 seconds, and they're representative of the state of the art.

With such a low Isp, barely getting past the heliopause in 40 years would require 100 times more fuel mass than spacecraft mass, a ratio that verges on impractical.[6] For a probe the size of Voyager 1 (722 kg), the total mass would verge on a hundred thousand kilograms if the mass of the fuel tanks were added.[33]

In spite of these drawbacks, the technology has a long history of use for missions within the solar system. It has reached a point where not much improvement can be made, but NASA is very familiar with implementing this technology and designing reliable systems.

The cost to implement a chemical propulsion system for an interstellar probe would be a little more than that of the average probe mission today because of the massive amounts of fuel required. Nonetheless, the cost would be very reasonable because the technology is so widely used and readily available.

There would be no cost or time to develop the technology, since it is already in use.

As mentioned above, even a fuel mass ratio of 100 would only be able to get the probe past the heliopause in 40 years, putting the

total mission length time at thousands of years.

Finally, safety would be as much an issue here as with a shuttle launch, since the propellant type would be exactly the same. The danger of an explosion or crash exists, but there are thoroughly tested safety mechanisms in use already.

## *5.2 Radioisotope Propulsion*

Radioisotopes release energy as they decay. A radioisotope rocket uses this energy to heat propellant and expel it out of a nozzle, generating thrust. Even though this is a promising type of propulsion, its specific impulse is still rather low for an interstellar mission. Propulsion systems based on radioisotopes are still in the conceptual design phase.[6] However, since radioisotopes are used as a reliable power, some of this research can be applied to radioisotope propulsion, reducing cost and development time.

### 5.2.1 Radioisotope Propulsion QTA Evaluation (see Appendix 11.1)

ISP: 1
Mass: 4
Reliability: 3
Cost to develop: 4
Cost to implement: 4
Time to develop: 4
Mission Time: 2
Safety: 4
*Total*: 3.05

### 5.2.2 Discussion

The cost to implement a radioisotope propulsion system for an interstellar probe is largely dictated by the cost of the radioactive source used for the mission. Many radioisotopes are expensive and difficult to obtain. Additionally, the power requirements of the probe will dictate the amount of radioisotopes needed for the mission, and therefore its cost. Since radioisotope propulsion has not been tested, time and money will need to be invested into making this a viable type of propulsion. Also, since the specific impulse is lower than desired (yet still greater than that of shuttle), the mission time would last for centuries, much longer than an average career or lifetime.

Finally, radioactive materials pose a safety risk that will need to be considered, adding additional hardware and technology. This will affect both the mass and cost of the mission.

## *5.3 Fission Propulsion (Solid Core)*

Fission is a process in which atomic nuclei are split apart, releasing energy. Radioactive elements such as Uranium, Polonium, and Plutonium are commonly used in fission. This process is used to heat up propellants such as hydrogen and exhaust the fluid through a nozzle.[6] Types of fission reactors include solid core and gas core. Gas core reactors have the potential to perform at higher levels due to increased temperatures of the plasmas yet solid core reactors have been studied to a greater extent.

### 5.3.1 Fission Propulsion QTA Evaluation (see Appendix 11.1)

ISP: 1
Mass: 4
Reliability: 4
Cost to develop: 4
Cost to implement: 4
Time to develop: 4
Mission Time: 2
Safety: 3
*Total*: 3.11

### 5.3.2 Discussion

Solid core fission reactors have a low specific impulse, though greater than Shuttle.[6] The technology has been proven theoretically but the United States has very little experience with implementing or testing it. The cost includes the infrastructure needed to test fission, as well as the expensive fuels that must be produced for use. This technology has been researched for some time now and it has already been tested outside of the U.S. Therefore, if the administration declared fission reactor research an area of priority, it seems reasonable that this technology could be developed in less than fifty years. Still, since the specific impulse is rather low the mission time would last for centuries, much longer than an average career or lifetime.

Lastly, safety is of high concern for the implementation of fission-based propulsion. The radioactive fuels would require new technologies to ensure safe operation, delivery, production and storage.

## *5.4 Fusion*

Fusion rockets are the second type of nuclear propulsion that utilizes the energy released from combining the atomic nuclei of two lighter elements to form one heavier element. As elements are fused together, tremendous energy is released that surpasses the splitting of heavy nuclei via fission. Furthermore, nuclear fusion works best with lightweight, non-radioactive atoms, such as hydrogen, which is fused together to form helium. Fusion of heavier elements is unproductive since it requires more input energy than is released. The immense energy released by fusion processes can be used to heat the propellant, which is hydrogen and the fused byproducts. These particles are accelerated and exhausted through the nozzle.

Considerable theoretical and experimental research has gone into fusion propulsion. In the 1970's, Project Daedalus laid out a very complete proposal for a fusion propelled interstellar mission. It was a significant step forward, and many of the key features for the fusion propulsion system are used to rank the rubric categories. Relevant information about the Daedalus project and how it was used for QTA is in the discussion section.

### 5.4.1 Fusion QTA Evaluation (see Appendix 11.1)

ISP: 3
Mass: 4
Reliability: 3
Cost to develop: 3
Cost to implement: 4
Time to develop: 3
Mission Time: 4
Safety: 4
*Total*: 4.00

### 5.4.2 Discussion

Nuclear fusion rockets have a very high projected specific impulse. They are more efficient because they have higher energy per mass fuel; thus the exhaust velocity is larger. Fusion rockets are limited by the molecular weight, $m_{atomic}$, of the byproducts

and the allowable temperature, T, of the reaction, as shown in the equation below:

$$I_{sp} = \frac{V_e}{g} = \frac{\sqrt{3k_B T / m_{atomic}}}{g}$$

where g is the acceleration due to gravity, $k_B$ is the Boltzmann constant, and $V_e$ is the exit velocity of the gas particles. Because of the vast heat released during fusion, the spacecraft is very efficient, and is within the bottom range for an interstellar mission to Gliese 581c. However, the tremendous heat released will affect material costs as newer, expensive materials are developed and used. This has an effect on the reliability, time to develop, and cost categories. Daedalus was also projected to have an $I_{sp}$ of one million.[16]

The mass of a fusion rocket is adapted from the Daedalus project. The payload of this mission was 450 tons, or $4x10^5$kg, which required 50,000 tons of fuel, or $4.5x10^7$kg. The total mass was $4.9x10^7$kg.[14] Daedalus would fall under a score of two. However, a small probe to Gliese would have lighter payload, which dramatically reduces the fuel and structure mass. Figure X graphs a relationship between mass ratio and distance traveled in the Interstellar Primer.[6] Judging by the curve for fusion rockets, there is not much benefit to increasing the mass ratio above 100 because it plateaus. Increasing the mass ratio would have a negligible effect on reducing the time to of travel and would only be detrimental to the mission by greatly increasing the cost. If a probe weighed only 100 kg, then the required fuel's mass would be 1000 kg. Taking into account the structural mass of the Daedalus probe and using a simple ratio, the structure mass would be ~70 kg. The structure will most likely not be this small in mass because the heavy magnets and laser equipment will not decrease in mass like the structure containing the fuel would. Nevertheless, we can estimate that the total mass would be on the order of thousands of kilograms.

There are many ideas, designs, and studies for a fusion rocket, and the reliability varies depending upon which approach is taken. Overall, there are no or negligible moving parts. The theory and many experiments are very well developed; however, a practical propulsion system has not been developed and tested. A key issue of controlled fusion is the confinement of the fuel during the initiation of the fusion process. Control and confinement of fuel are major factors in the reliability of a technology. While this leads to uncertainty in reliability, there is also encouragement in the fact that many techniques are possible and it's a matter of more research and engineering. One method is magnetic confinement fusion, MCF, which is based upon the sun's fusion process. While this is capable technology, it requires super heating propellants using plasma and large, massive magnets for containment; not a good choice for a propulsion system. The most promising method is Inertial Confinement Fusion. ICF uses a lighter electron beam to initiate the fusion of fuel pellets.[16] The initial fusion reaction requires significant energy. One way to begin the fusion reaction is through the use of antimatter catalyzed fusion. ACF uses a very small amount of antimatter to start the fusion process. This antimatter-fusion system creates more reliability, safety, technology and mass concerns. The QTA is judged primarily upon the use of Inertial Confinement Fusion, which is also what the Daedalus was designed to use. Fortunately, fuel candidates include hydrogen, deuterium, tritium, helium, and boron. They are lightweight, stable, and they are mostly either abundant resources or easily manufactured. Fusion is feasible;

however, robust reliable technology is a matter of time and creativity.

The cost to develop was given a three because more money is needed to develop fusion technology than the current NASA budget. It would take a shift in focus and allocation of resources to pursue fusion research. It would also call for partnerships and contracts with scientific foundations in order to harness their current knowledge, resources, and technologies. To NASA's benefit, the cost to develop is shared by countless private research groups as well as other government funded programs. Across the board, more money is needed to pick up the pace and develop this technology if it were chosen to propel an interstellar probe to Gliese.

Implementation costs are likely to be less than development costs. The development of fusion technology is making slow progress and requires constant funding. When the technology and designs for the actual spacecraft are ready, the materials should not be excessively expensive. Potentially high costs could come from the development of new lightweight materials that can withstand the extreme heat. The fuel costs can be high or low, depending upon the fuel chosen. Hydrogen is the most abundant element in the universe. Boron and deuterium can be extracted from seawater and tritium can be manufactured. The Daedalus probe proposed deuterium and helium-3 because the reaction releases alpha particles and protons, which can be deflected by a magnetic nozzle for greater propulsion. Unlike other fuels, which waste heat from unused neutron particles and excess energy from gamma rays, this method saves mass and energy. Unfortunately, helium-3 is harder to ignite. It is also rare on earth, but can be mined from the moon or collected from the atmospheres of Uranus and Jupiter. Choosing this fuel would be more costly, but more efficient.[16]

Fusion technology is currently making slow progress. It is not necessarily due to a lack of interest, but scientific obstacles. Assuming NASA, other government agencies, and private industries chose to pursue fusion technology for the purposes of an interstellar probe, with the needed funding and allocation of resources, time and focus reflected by the QTA and previous discussion, fusion technology could possibly be developed within the next couple generations. Furthermore, antimatter-fusion and ramjet fusion benefit alongside the development of fusion technology. Not to mention, the development of fusion would have far reaching impacts other than propulsion.

By using Figure 26, trip duration is estimated to take approximately 191 years (including signal return time) using fusion at .01g acceleration w/ a mass ratio of 100. This is calculated by dividing the distance of Gliese, 20.5 ly, by that of Alpha Centauri, 4.3 ly and multiplying by the 40 years it would take to get to Alpha Centauri displayed on the graph. Two ways to reduce the travel time, would be by increasing the mass ratio (as seen on the graph), or increasing the acceleration. As discussed before, increasing the mass ratio is not beneficial. These numbers are confirmed by the Daedalus probe, which was estimated to fly at 12% the speed of light with a $10^6$ second $I_{sp}$. At this velocity, it would take 191 years to fly to Gliese, including signal return time.

Safety for fusion propulsion is actually quite good. There are no radioactive fuels, unless a very small amount of radioactive material is used for fission reaction to start the fusion

reaction. The simple elements for fusion are not harmful. Upon fusion, some byproducts can release gamma rays, which are potentially harmful; however, this will only occur in space when the unmanned craft is a safe distance away.

## *5.5 Nuclear Pulse Fission*

An alternative to nuclear fusion rockets is nuclear pulse propagation. This method primarily has relied upon nuclear fission explosions to detonate outside of a spacecraft, thus the allowable temperature is much higher.[20] The spacecraft would be propelled forward by the shock wave.

### 5.5.1 Nuclear Pulse Fission Evaluation (see Appendix 11.1)

ISP: 2
Mass: 1
Reliability: 3
Cost to develop: 4
Cost to implement: 4
Time to develop: 3
Mission Time: 1
Safety: 2
*Total*: 2.24

### 5.5.2 Discussion

In the 1960's, Project Orion was the first attempt to implement this idea. In 1965, Freeman Dyson calculated that nuclear pulse could propel a vehicle to speeds of 1,000 to 10,000 km/s, taking a century to a millennium to reach the nearest star. A theoretical maximum specific impulse of $10^6$ seconds was also calculated, although tens of thousands of seconds is more likely.[14]

The mass of Orion was $3.6 \times 10^{10}$kg. This mass is used for the QTA of pulse fission propulsion.

Testing calls for nuclear explosions, so it would be very difficult and potentially costly considering nuclear test restrictions. Also, the fission atomic explosion releases great amounts of radiation and could be hazardous if performed near earth's atmosphere, not to mention the public's history of deep disapproval.

As for reliability, the original Orion plans for such a propulsion system did not have any inherent flaws. The early stage tests showed a promising future, if not for the dangers of atomic radiation. The theoretical and conceptual work is extensive, although much development and testing is needed. Furthermore, the pusher plate that absorbs the shock wave is a moving part that would be subject to extreme heat and shock, which would be a considerable challenge to keep in tact for a long mission such as Gliese 581c.[14]

## *5.6 Nuclear Ramjet*

The Interstellar Nuclear Ramjet uses an electromagnetic scoop to collect hydrogen and use it for nuclear fusion. The fusion process is then used for a propulsion system.

### 5.6.1 Nuclear Ramjet QTA Evaluation (see Appendix 11.1)

ISP: 5
Mass: 3
Reliability: 2
Cost to develop: 2
Cost to implement: 3
Time to develop: 2
Mission Time: 4
Safety: 4
*Total*: 3.24

### 5.6.2 Discussion

The ramjet's infinite specific impulse makes it a prime choice for interstellar missions. Its

large $I_{sp}$ is due to the fact that the ramjet collects its fuel throughout travel. The effective mass ratio is only one. This greatly reduces the overall initial mass of the spacecraft and cuts fuel costs. The structural mass, however, can be quite heavy. Since the density of space is projected to be only .01 to 1 atom of hydrogen per square centimeter, a large electromagnetic scoop is required to collect an adequate amount of fuel.[20] It is estimated that a one ton (~900 kg) probe would require 6000 km scoop diameter in order to go 5.9% the speed of light.[20] The size and mass of the collecting scoop depend upon the velocity of the probe. The higher the velocity, the smaller size and weight of the total craft.[20] An interstellar probe to Gliese 581c is estimated to have a payload of under 100 kg. Using Newton's second law of motion, there are two possible effects for this decrease in mass. The acceleration could increase nine fold (from a previous mass of ~900 kg), resulting in a more efficient, smaller, scoop yet a more robust structure to handle the acceleration (increasing cost). Second, the acceleration can remain the same, which would yield a lower thrust from smaller, not as robust scoop. The mass of these two options is estimated to be the same (lighter material is balanced by more of it) and is approximated to be on the order of $10^4$ kg.

The reliability of a ramjet is difficult to discern due to its infancy. The theoretical work is solid for the most part. Hydrogen is a part of the interstellar medium, but its actual density en route to Gliese is unknown. Furthermore, interstellar hydrogen is neutral and would need to be charged by the spacecraft before collected. These factors make for a high level of uncertainty, warranting the ramjet a reliability of two.

The cost to develop ramjet propulsion would require more money from the government since the technology is so young. Significant research, time, and testing would be required if a ramjet system was chosen to be developed within a reasonable amount of time. Furthermore, ramjets rely on reliable fusion technology, which has not been developed and is a very costly pursuit. Once developed, the implementation cost would still be very large; however, it should not be as much as the cost to develop. A large scoop would also require more than a few missions to assemble in space. For these reasons, the development and implementation costs were ranked as a two and a three.[6]

The time to develop depends upon fusion technology as well as a practical method of collecting hydrogen. While there has been significant research, it will take much development of the underlying science, and then the safe, reliable application to a propulsion system. The time to destination varies upon the size of the scoop, which is a direct factor of cost. Using the information from Landis' report, a rough estimate can be derived.[20] At best, a probe weighing 100 kg, nine times less than that of Landis' projection, the acceleration will increase nine-fold. The time to destination is proportional to the square root of one over acceleration:

$$t \propto \sqrt{\frac{1}{a}}$$

This means that the time is cut to one third of Landis' projected time, which was based upon a velocity of ~6% the speed of light. The time it would take to travel to Gliese at 6% the speed of light is 342 years. Divide this by three and the projected time for a 100 kg probe to reach Gliese is 114 years.

Like a straight fusion system, safety is not as large of a factor as it is with fission propulsion because the fuel and byproducts are not radioactive. There is a tremendous amount of energy released upon detonation, and detonation will not occur until the spacecraft is a safe distance away from earth's vicinity.

## *5.7 Lightsails*

A lightsail is exactly like a wind-powered sail except that it gains momentum from photons hitting it as opposed to air particles hitting a wind sail. Since the momentum transferred from light is much less than that from air, lightsails are likely to be on the order of kilometers across.

### 5.7.1 Lightsails QTA Evaluation (see Appendix 11.1)

ISP: 5
Mass: 4 [17]
Reliability: 4
Cost to develop: 4
Cost to implement: 4
Time to develop: 4
Mission Time: 2
Safety: 5
*Total*: 4.05

### 5.7.2 Discussion

Since a lightsail needs no fuel, its specific impulse in infinite. The thrust, however, would taper off to zero as the probe moves away from the sun, at which point the sail could be dropped and another form of propulsion used. The sail could also be propelled by a powerful laser, in which case the sail could still provide thrust far outside the solar system.

Mass estimates came from a study at Marshall Space Flight Center, where lightsail models built by three different companies were tested at Plum Brook Station. The models had sail densities around 10-30 g/m$^2$ including the support vanes[17], and the sail used for an interstellar mission is likely to be around a kilometer wide, using the lightsail design for NASA's Interstellar Probe[29] and Robert Forward's proposal[25] as a baseline. That puts the sail's mass on the order of tens of thousands of kilograms.

The sail would have no moving parts to detract from its reliability, except those used to initially unfold the sail. The technology has been proven in lab tests like the one at Plum Brook[17], but it has not been used as a main source of propulsion for any spacecraft to date.

Once the technology has been developed, the cost of implementing it should be comparable to that of NASA's current probe missions. There is nothing inherently expensive about the huge sail compared to NASA's other projects, once methods of manufacturing it have been developed. Suggested materials include LiF and $CaF_2$ dielectric films, nothing particularly rare or costly.[20]

The cost of development would just be the cost of several more investigations into lightsail technology on a scale comparable to the one at Plum Brook[17], and perhaps some launched from the space station, to refine and experimentally verify the technology. NASA would need to fund a series of these investigations and not cut too many of them before results are obtained, so lightsails would need to reach a certain level of priority with NASA.

Since model light sails have already been tested, the time to develop the technology should be on the scale of decades.

In theory, a light sail can accelerate as long as the photons transferring momentum to it are moving faster than the sail. That means its speed approaches the speed of light if allowed to run indefinitely, but realistically, a very optimistic maximum speed would be a tenth the speed of light, but a fraction of that is more likely.[25] For a star about 20 light-years away, that puts the mission timescale on the order of centuries.

Since lightsails don't involve flammable or explosive propellants, or propellants of any sort, safety is not much of an issue with them. The worst they could do is fall on someone, or else the launch vehicle could explode or crash, but those things could happen no matter what propulsion technology is used for the probe.

## *5.8 Antimatter*

In addition to normal sub-atomic particles that surround our daily lives, like protons, there also exist very rare particles called antimatter, such as antiprotons. When these two types of particles collide, they completely annihilate each other, releasing energy greater than any nuclear or chemical reaction. Antimatter propulsion is an advanced concept system that harnesses the incredible amount of energy released from a matter/antimatter detonation. One form of efficient antimatter propulsion is beam core propulsion. This system sustains antiproton annihilations, producing gamma rays and pions that can be exhausted through a magnetic nozzle at near the speed of light.[1]

### 5.8.1 Antimatter QTA Evaluation (see Appendix 11.1)

ISP: 4
Mass: 3
Reliability: 2
Cost to develop: 3
Cost to implement: 1
Time to develop: 2
Mission Time: 5
Safety: 3
*Total*: 3.00

### 5.8.2 Discussion

Some uncharged byproduct particles and the gamma rays cannot be used for propulsion; however, the antimatter reaction is the highest energy density fuel. The specific impulse of such a system greatly depends upon the thrust level. Beam core technology, with a low thrust level, can yield up to, and perhaps even greater than, a ten million second specific impulse.[6]

Because of its prodigious energy density, the fuel mass for a mission is relatively small. Only ~1 kg of fuel is projected for trip to Alpha Centauri. According to the performance comparison graph, shown in Fig. 4, a mass ratio of approximately thirteen ($M_i/M_b$) and an initial acceleration of .05g, would yield a trip duration of *sixty-nine* years. For a 100 kg payload probe, this equates to a mass of 1400 kg, without the structure mass. The probe would reach a final acceleration of .65g. The structure would need to be robust enough to withstand the larger acceleration, this increases the cost and the mass. Furthermore, the vehicle would require heavier machinery for the magnetic nozzle and the equipment to levitate the antimatter. Furthermore, the structure must be very long since the byproducts speed out of the nozzle at near the speed of light.[1]

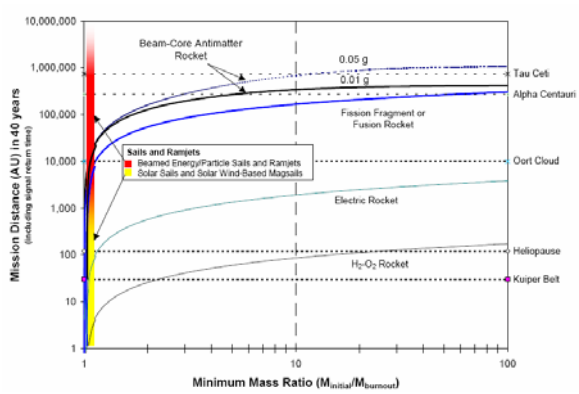


**Figure 26. Mission Performance Comparison.**

The reliability of an antimatter spacecraft is dominated by its uncertainty. The theory is well developed and there is extensive research. Antiprotons have been created and even combined to create an anti-hydrogen molecule. Safe storage of antimatter is essential, because if it comes in contact with regular matter anywhere before the combustion chamber, it will annihilate prematurely. Fortunately, antimatter has successfully been stored in small quantities.[6] An antimatter drive has never been built and tested. Creating a sustainable and stable drive requires much more work. There is also major risk in using such volatile fuels; however, the technology looks promising for the future. For these reasons, antimatter propulsion receives a reliability of two.

Antimatter is a serious safety risk, though this should not exclude it from consideration. Technology is already developed to hold antimatter safely, and it is a matter of time before safe reliable equipment will support antimatter in a propulsion system.

Antimatter is intensely researched. Currently, only very small amounts of antimatter can be made and stored. It will take a significant amount of time for large cheaper volumes of antimatter to be available, and even longer for it to be implemented into a propulsion system. If NASA encouraged government and private company research, for the specific focus on an interstellar mission, a propulsion drive could be invented, tested, and launched within a couple centuries, thus receiving a development time score of two.

The cost to develop is not necessarily as large of a cost as it is to implement, at least to NASA. Since the research is spread out so much around the world, antimatter's development is not hinged solely upon NASA's monetary contributions. Currently, the cost to create one gram of antimatter is 62.5 trillion dollars.[1] If this cost does not decrease by the time of implementation, then NASA would need to spend $8.06 quadrillion to build a 1300 kg fueled probe. That is 124 times the world's Gross Domestic Product ($65 trillion).[56] By this time, the cost per gram would need to decrease dramatically.

# 6 Power Systems

## *6.1 Photovoltaics*

Photovoltaics are solar cells that convert light energy into electricity by allowing incoming photons to separate electrons from their atoms and forcing the freed electrons to flow around a circuit according to the electrical charge gradient.

### 6.1.1 Photovoltaics QTA Evaluation (see Appendix 11.2)

Specific energy: 1
Lifetime: 1
Reliability: 5
Cost to develop: 5
Cost to implement: 5
Time to develop: 5
*Total*: 3.15

### 6.1.2 Discussion

Photovoltaic cells tend to convert around 10% of the light energy that hits them into electrical energy, so in the space between stars where not much light is available, the power output per mass plummets.[1] Huge, heavy solar arrays would be necessary to power a purely photoelectric vehicle from one star to another.

The drop-off in power outside the solar system means the effective lifetime of the system would only be as long as the probe is close enough to the sun. Decades would almost certainly be sufficient for the probe to exit the solar system, and for solar panels to lose their usefulness.

Nonetheless, photovoltaic technology has proven its reliability on a multitude of space missions within the solar system, as well as in long-term solar power installations on Earth. The basic photoelectric cell setup is simple and requires no moving parts.

The technology is currently well developed, but if it were to be used on an interstellar mission, a few years should be allotted to improve efficiency so that it can be useful as far as possible from the sun. Once the probe goes much beyond the solar system, however, a different technology would need to become the probe's primary source of power, and the solar arrays would probably be jettisoned to facilitate acceleration.

Because the technology is so readily available and widely used, the cost to implement it would be comparable to the cost of using photovoltaics on other current probe missions, which do use photovoltaics more often than not. Further research to improve the technology should not cost more than a typical NASA research project, especially since NASA has already funded a multitude of photovoltaic studies.[1]

## *6.2 Battery Power*

A battery, also known as a galvanic cell, is an electrochemical cell that stores chemical energy and converts it into an electrical form. A battery is a sense series of voltaic cells. As a result there are many different types, of batteries each comprised of variable chemicals. Every battery has two terminals, one negative and one positive. Electrons collect on the negative terminal and if a wire is connected between the positive and negative terminals, the electrons will flow from the negative and positive terminals, which is also known as shorting the battery. Normally, the battery powers a load that is configured in between the sequence. This load can come in the form of a motor, or any type of electronic circuit. Batteries have been well established in the scientific arena and are readily available to consumers.

### 6.2.1 Battery QTA Evaluation (see Appendix 11.2)

Specific energy: 1
Lifetime: 1
Reliability: 5
Cost to develop: 5
Cost to implement: 5
Time to develop: 5
*Total*: 3.15

### 6.2.2 Discussion

When considering battery capability for in space flight application, specific energy and energy density, discharge rate, charge retention, shelf life, operation temperatures need to be taking into account. . Batteries' specific energy can range from 90 – 30 W-h/kg and is dependent upon the chemical makeup. Primary batteries such as

Lithium/Monofluoride (Li/CF), Lithium/ Thionyl, and Chloride (Li/SOCl ), which have all been tested at the Marshall Space Flight Center (MSFC), are useful in short duration specifically in providing electrical power to the space station. Primary batteries are relatively high in energy density and possess substantial reliability. Secondary batteries do not posses the ability to discharged and then recharge, like those chosen for primary sources. The main use of secondary batteries are spacecraft, satellite, and other long-term applications. Nickel/Cadmium (Ni/Cd), Nickel/Metal Hydride (Ni/MH), and Bi Polar-Lead Acid (Bi-Pb/Acid) are few of the Secondary batteries that have been assessed by the MSFC. Because of the chemical nature of batteries, they lose performance in extreme temperature and pressure conditions. As a result, battery power sources should be tested in an environment similar to that in which it will operate.

It has been shown that over a period of time the insulator within a Ni-Cd battery often develops holes. These holes allow the cell to grow crystalline shorts that provide a conduction path between the positive and negative electrodes of the cell. This path essentially shorts out the cell. If this were to occur it would be necessary to blow open this short with a high current pulse before the cell will again accept charge .This is not desirable in space flight application. The continued study of battery application in space flight is promising and has proven to possibly be highly energy efficient.

Compared to other power sources, batteries are considerably more dependable because there are no mechanical moving parts. Also, because of their nature, that can be several back up batteries that could be implemented to represent an entire system.

## *6.3 Fuel Cell Power*

A fuel cell is electrochemical energy conversion device that convert Fuel cells Hydrogen and Oxygen into electricity. In what inventor, Sir William Grove, referred to as reverse electrolysis; electricity is created when pure Hydrogen and Oxygen are combined.

Once hydrogen is added to the fuel cell, catalysis on the anode, the negative post of the fuel cell, transforms the hydrogen into both a positively charged ion as well as negatively charged electrons. The hydrogen ions begin to migrate through the electrolyte to the cathode, the positive post of the fuel cell, where it bonds with oxygen and electrons to produce water. The reaction of a single fuel cell can produce 0.7 volts. In order to reach a reasonable level voltage to be utilized for energy, single fuel cells must generate fuel cell stacks. Fuel Cells utilize 80 percent of the energy content of hydrogen into electrical power.

The idea of using fuel cells in aerospace applications is not new. The elimination of combustion and moving parts allows for fuel cells to run continuously for longer periods of time and make it an idea power source. Even though fuel cells can operate for extended periods of time , the durability of fuel cells is weakened they are constantly started and stopped and operated at high temperatures. Fuel cells that are developed today are built for sea level atmospheric pressure conditions. John Del Frate the manager of the Helios unmanned vehicle at Dryden Research Center says, “In a sense, it’s an automotive-type fuel cell system but there are some challenges, particularly the higher you go.” Systems designed for higher altitudes (over 50,000 feet) and space travel would have to endure low pressures and temperatures of about –110F. As a result,

there is a lot of room for research and development. Currently, researches are looking to develop a membrane that can function at temperatures greater than 100 degrees Celsius as well as sub-zero conditions. It is important that the developed membrane remains stable because under present conditions, the membrane degrades particularly as temperatures rises.

### 6.3.1 Fuel Cell QTA Evaluation (see Appendix 11.2)

Specific energy: 2
Lifetime: 1
Reliability: 5
Cost to develop: 5
Cost to implement: 5
Time to develop: 5
*Total*: 3.23

### 6.3.2 Discussion

Based on the Qualitative Trade Analysis, fuel cells received a 8.4 out of 13. Since they are relatively common in different scientific applications, there is less of a learning curve when doing research to improve their output in extreme weather conditions. Because of their inability to operate in space conditions, fuel cells received a low score on the reliability and time to develop. However, since there is no moving parts and the overall technology is generally established, the reliability is considerably higher than other less known systems with moving mechanical components. Based on current technology, fuel cells are most efficient when operating at 1 kW-h/kg. This number is considerably higher than that of a battery, and the reason used in many applications. However, when comparing fuel cells against other power systems for deep space travel, this number is low and needs to increase if fuel cells are going to be seriously considered as a primary power source.

## *6.4 Radioisotope Power*

For an interstellar mission, the power system must supply electricity to scientific instruments on-board and also provide heat to instrument components for long-term, reliable operation.

Radioisotope power is formed from the heat of decaying radioisotopes such as Plutonium-238. The specific energy of radioisotope power systems is relatively low. Therefore as mission length increases, the mass of the power system also increases significantly.[6] Radioisotope power has the potential to provide between 500 Watts - 10 kW of power, or 600 kWh/kg over 16 years with a power range between 0.076-0.141 kW for an Advanced Radioisotope Power Source. The lifetime of the system is determined by the selected radioisotope's half life. The radioisotope should be chosen to have a half-life greater than the mission time so that the power supplied does not drop below the requirements of the mission.

### 6.4.1 Radioisotope Power QTA Evaluation (see Appendix 11.2)

Specific energy: 3
Lifetime: 2
Reliability: 5
Cost to develop: 5
Cost to implement: 5
Time to develop: 5
*Total*: 3.85

### 6.4.2 Discussion

Radioisotope Thermoelectric Generators (RTG) are reliable, well developed and can contain few to no moving parts. RTGs convert the heat provided by decaying radioisotopes to electricity. The reliability of RTGs has been demonstrated via use on the Pioneer, Voyager, Galileo, and Cassini probes.[6] Since this technology has been

proven by use in other probe missions, the development time is less than 10 years. Similarly, the cost to develop the technology for an interstellar mission is reasonable. The cost to implement this technology depends primarily on the amount power required by the probe. This dictates how many radioisotopes are necessary and radioisotopes can be expensive. General concerns of radioisotope power that need to be addressed for any mission are safety, public support, and the need to protect on-board instruments from radiation.

## *6.5 Fusion Power*

Fusion reactions can potentially release 3 x $10^{14}$ J/kg, much more power than a fission power system that releases 8 x $10^{14}$ J/kg [16] The immense heat liberated from the reaction can be used for propulsion (see above) or can be converted into electrical energy.

### 6.5.1 Fusion Power QTA Evaluation (see Appendix 11.2)

Specific energy: 5
Lifetime: 5
Reliability: 3
Cost to develop: 3
Cost to implement: 3
Time to develop: 4
*Total*: 4.00

### 6.5.2 Discussion

Because of the large energy per mass of fuel that fusion possesses, the specific energy can reach up to a maximum of $10^8$ kW-h/kg.[6] The lifetime is also very good as long as some fuel is conserved for the entire trip's duration. The technology does not depend upon available sunlight like solar power does. If a ramjet electromagnetic scoop is developed, then the collection of hydrogen could be utilized for fusion power as well as propulsion. This effectively ensures a longer lifetime, assuming that an adequate amount of hydrogen is available.

Reliability was based upon the current development of fusion. There are no significant moving parts and the theory is well developed. There is significant uncertainty due to the lack of positive energy output in fusion experiments so far. There are also issues with the confinement of the fuel and the initiation of the fusion process; however, there are many approaches to solving this, including magnetic and inertial confinement fusion, and antimatter catalyzed fusion for initiation.[16] There is promising work in fusion development and many reliable power technologies are being researched and tested.

The time to develop is solely dependent upon fusion technology. If NASA, its partners, and other government agencies decided to pursue this technology more intensely for the purpose of spacecraft power, it is estimated that the time to develop would be within a century.

The cost to develop fusion power is shared by countless other governments and private organizations. Once the technology is developed, NASA's challenge would be to make it space rated – as light, durable and safe as possible.

The cost to implement and develop fusion technology is rated the same as it would cost NASA to implement and develop fusion propulsion. More money is needed by the government to develop the technology, as well as a large shift in focus and re-allocation of human and material resources. Again, the cost to develop is a very expensive and long term investment that is fortunately shared by many agencies and

organizations. One of the greater costs that would be unique to NASA would be making the technology light weight, safe, and robust for a long term mission to Gliese 581c. Implementation costs depend greatly upon the fuel chosen and the amount of that fuel. It also depends upon the cost of new materials developed to withstand the tremendous amount of heat generated from fusion.

## *6.6 Fission Power*

Fission power sources convert the heat produced by splitting atomic nuclei (such as Uranium-235) to electricity. Fission has a higher specific energy than radioisotope power, up to 3,000 kWh/kg, and is therefore able to provide higher power levels than radioisotope power. Gas core reactors provide an order of magnitude higher power output than solid core.[6] Since it has a higher specific higher power, less mass is needed, reducing mission cost. The lifetime of a fission nuclear reactor depends on the amount of fuel available, potentially lasting for hundreds of years.

### 6.6.1 Fission Power QTA Evaluation (see Appendix 11.2)

Specific energy: 4
Lifetime: 2
Reliability: 4
Cost to develop: 4
Cost to implement: 4
Time to develop: 4
*Total*: 3.54

### 6.6.2 Discussion

Fission power has been heavily researched. Most of this research in the United States has been theoretical or small-scale experimental research. In 1965 the SNAP-10A reactor flew in space. Since then Russia has launched fission reactors but the US has not. There public concerns about launching radioactive materials are high. However, with increased public support fission could be a reliable source of power for spacecraft. The time and cost of development would be reduced since this technology is past the proof-of-concept phase. Time would be needed to develop measures to protect the probe components from radiation as well as experimental testing of launching this technology into space. The cost to implement fission power for an interstellar mission would depend on safety measures, amount of fuel, and the method used to create fission.

## *6.7 Beamed Power*

Beamed power is just like photovoltaics except that the light comes from a powerful laser on Earth instead of the sun or another star.

### 6.7.1 Beamed Power QTA Evaluation (see Appendix 11.2)

Specific energy: 2
Lifetime: 3
Reliability: 3
Cost to develop: 4
Cost to implement: 3
Time to develop: 4
*Total*: 3.00

### 6.7.2 Discussion

The power output of the system depends heavily on the kind of power-beaming facility Earth can offer, but judging by the photovoltaic technology that would be used on the probe, the output should be in the kilowatt-to-megawatt range.[6] Per kilogram, the specific energy would not be very high, but it would still be better than simple solar cells.

Since the Earth-based beaming facility can have as much maintenance work as it needs, and the probe's power equipment is based on well-established photovoltaic technology, the lifetime of beamed power will be about the same as that of photovoltaics.

The same as standard photoelectric cells, the cells that receive beamed power have no moving parts, so their reliability is high, but the reliability of the beaming facility is questionable because the technology has not been tested. No facility exists that could supply a significant amount of energy to an interstellar mission through beaming.[6] Fortunately, this part of the power system is easy to monitor and repair because it stays on Earth, assuming that Earth remains interested enough in the mission to maintain the facility.

The time to develop this technology refers almost entirely to the time to develop a beaming facility that is powerful enough. This involves improving the efficiency and increasing the scale of laser technology, which is a reasonable endeavor but would require NASA to focus more on lasers than it does currently. Given an appropriate amount of attention, decades should be sufficient for the necessary improvements, looking at how laser technology has improved historically.

Once the technology is ready, the cost to implement it will be significant, since NASA would need to build a laser the likes of which the world has never known. The optics, power sources, and simply the architecture of the facility would be monumental. The nation has built more expensive things, but NASA would probably need more money to do it.

The cost to develop the technology does not have to include the cost to build the kind of facility that would ultimately be needed. The technology can be developed and tested on a smaller scale, but as stated above, NASA would need to focus more on laser technology than it currently does.

## 6.8 Antimatter Power

The universe is made up of matter and matter's counterpart, antimatter. When particles of these two types collide, they completely annihilate each other, releasing energy greater than any nuclear or chemical reaction. Antimatter annihilation has the potential to generate $9\times10^{16}$ J/kg, two orders of magnitude greater than fusion.[1] The joining of matter and antimatter releases extreme amounts of heat, which can be converted into electrical energy to power a space probe.

### 6.8.1 Antimatter Power QTA Evaluation (see Appendix 11.2)

Specific energy: 5
Lifetime: 5
Reliability: 2
Cost to develop: 4
Cost to implement: 1
Time to develop: 2
*Total*: 3.62

### 6.8.2 Discussion

An antimatter power system has an excellent energy density of up to $2\text{x}10^{10}$ kW-h/kg.[6] The lifetime of an antimatter system could be hindered by the amount of antimatter fuel and the deterioration of material due to extreme heat. If enough antimatter can be produced and a durable enough material developed, then the lifetime of an antimatter power system can last thousands of years.

Its reliability was given a two, mostly because of how young and therefore uncertain any practical antimatter

technology is. Theoretically, the concept is very developed; however, there are many technical challenges that question antimatter's reliability. Storage of antimatter is a very delicate process. Electromagnetic fields have been used to store very small amounts of antimatter, but nothing near the order of hundreds or thousands of kilograms, the amount needed for a power/propulsion antimatter system.[6] Furthermore, control of the actual annihilation of antimatter with matter to use as a source of electricity has not been developed. The storage and the control of an antimatter system give reason to rank the system a two.

Low cost, high volume antimatter will not take place overnight, and neither will the technologies to store and control antimatter. While the concepts for such a power system have been extensively experimented, the practical use of antimatter as a power source in a space probe is over a century away.

The cost to develop this technology would be shared by many organizations and would also be spread out across many years. NASA would not be the sole financial provider for antimatter research, and thus the cost develop is ranked as a four. NASA should wait to utilize the technology when it was in a well developed stage. NASA's challenge would then be to design the power system for a spacecraft, making it as lightweight, robust, and cost efficient as possible.

The cost of antimatter is currently ~$62.5 trillion per gram. The materials that can withstand the tremendous heat released from annihilation would also contribute to implementation costs.[1]

# 7 Autonomous Systems

## *7.1 Communications System*

Communications between the earth and spacecrafts becomes increasing complicated with the distance separating the two. These complications center on frequency choice, pointing capabilities and available power. Higher frequencies allow for greater bandwidth which means a higher data rate.[2] The trade-off to using higher frequencies is a greater power requirement. The pointing capabilities of the spacecraft will determine the achievable gain. Increasing the gain has the benefits of raising the signal to noise ratio and narrowing the beam, meaning more power is deposited on receiving antenna. However, higher gain requires higher frequency the consequences of which were discussed above, or increasing the size of the onboard antenna which will increase complexity and cost.[6]

Traditionally, the only form of communicating with spacecraft was with radio frequency (RF). However, laser communications systems have recently been developed for space based communications. Lasers have the capabilities of optimizing many of the restraints on an interstellar mission. They would decrease antenna size, weight, cost and beam width while potentially increasing data transfer rates.[27]

Another possibility for solving the distance problem is relay crafts which would be positioned along the path of travel between the interstellar craft and earth. Using relay crafts would cut down on path loss and be able to amplify the signal as it is passed on through each craft. However, adding any number of spacecraft to a mission increasing the complexity and cost of the mission. The relay craft could however be used for

multiple missions provided they have sufficient lifespans.

Using an RF system has the major advantage being already developed for spacecraft leaving earth's orbit. However, considering the advances made with laser communications in the past decade, further research and development in that area would most likely be profitable for the design and deployment of an interstellar probe.

## 7.2 Guidance and Navigation

The autonomy required of an interstellar probe will require that the craft be able to determine its position both in relation to the earth and in the space through which it is traveling. The craft will also be required to correct its trajectory and avoid obstacles on a nearly entirely autonomous level. Options for position determination include star trackers, sun/earth sensors, and inertial measurement units (IMUs).[6] Sun or earth sensors will only be useful while the craft is within the solar system, after which point it will be entirely dependent upon the star maps and IMUs. The craft would be able to function from the initial stages without the sun or earth sensors, however, their low weight and power consumption compared to other systems makes them a viable option Also, sun sensors are capable of providing both attitude and position information and may be able to help the star mappers orientate themselves through the early stages of the mission. A summary of these systems is shown in Table 12.

Star scanners are one of two types, either spinning or stable. A spinning star scanner is used if the craft is required to spin for pointing or stabilization purposes. Both types basically function in the same manner. After scanning the field of view (FOV), and repeatedly detecting the same star, the craft is able to determine its attitude. Star mappers function in a similar manner but locate multiple stars and are able to provide both attitude and relative position.

The IMUs provide the spacecraft with data on any acceleration, enabling the spacecraft to determine its position and attitude relative to a known reference position and attitude. This information can be used on the craft and also sent back to earth. The velocity and position of the craft can be determined from earth by monitoring the Doppler shift of the received signal.[6]

Most spacecraft currently in place in within the solar system have multiple instruments for guidance and control. IMUs are the most accurate of those discussed here, however they also have the highest mass and power needs. Sun sensors have the lowest mass and power needs but also provide the least functionality for an interstellar mission. Since mass and power for star mappers and star trackers are very similar, mappers would be more useful then trackers. A combination of these instruments will be required for most missions,

**Table 12. Summary of Guidance and Navigation Instruments[2]**

| Sensor | Performance Range | Weight (kg) | Power (W) |
|---|---|---|---|
| **IMUs** | Gyro drift rate=.0003°/hr to 1°/hr; Accelerometer linearity= 1to 5 x $10^4$ g/$g^2$ over the range 20 to 60 g | 3 to 25 | 10-200 |
| **Star Scanners and Mappers** | Attitude accuracy=1arc sec to 1 arc min, i.e. 0.0003° to 0.01° | 3 to 7 | 5 to 20 |
| **Sun Sunsors** | Accuracy=0.005° to 3° | 0.5 to 2 | 0 to 3 |

interstellar or otherwise to ensure accurate, consistent and constant guidance and navigation.

### 7.2.1 Spin Stabilization

#### Passive Control

One method of passively stabilizing the spacecraft is to keep it constantly spinning about the axis of largest moment of inertia. Spinning spacecraft resist small disturbances, although internal imbalances can cause nutation and precession. Navigational sensors on a spinning spacecraft are the line scan type, mounted so that they scan around as the spacecraft rotates.[6]

##### *7.2.1.1 Spin Stabilization QTA Evaluation (see Appendix 11.3.1)*

Accuracy: 2
Power Requirements: 4
Reliability: 5
*Total*: 11/15

### 7.2.2 Discussion

As a passive ACS, spin stabilization has an accuracy towards the lower end of the scale. While it has low power requirements and high reliability, spin stabilization also makes a spacecraft more difficult to reposition and uses large amounts of propellant.

### 7.2.3 Three-Axis Control

#### Active Control

The three-axis method of control uses actuators, such as momentum reaction wheels, control moment gyroscopes (CMG), or thrusters, to control spacecraft pointing and attitude. Three-axis control involves more overhead than spin stabilization, in terms of mass, power, and complexity. However three-axis control also allows much higher precision pointing and greater maneuverability.[6]

##### *7.2.3.1 Three-Axis Momentum Bias (One Reaction Wheel)*

A momentum bias system is similar to the spin stabilization method of control. A reaction wheel spins normal to the spacecraft's plane of orbit, causing gyroscopic stiffness that resists disturbances in the yaw direction.[23]

###### *7.2.3.1.1 Three-Axis Momentum Bias QTA Evaluation*

Accuracy: 3
Power Requirements: 3
Reliability: 4
*Total*: 10/15

##### *7.2.3.2 Three-Axis Zero Momentum (Three Reaction Wheels)*

In a zero momentum system, disturbances to the spacecraft's attitude cause the momentum wheels to spin up or slow down. When a wheel is saturated at a maximum or minimum spin rate, external torquers or thrusters are used to dump momentum and return the spacecraft to the correct attitude.[8]

###### *7.2.3.2.1 Three-Axis Zero Momentum QTA Evaluation*

Accuracy: 4
Power Requirements: 3
Reliability: 4
*Total*: 11/15

#### *7.2.3.3 Three-Axis Zero Momentum with Control Moment Gyroscope (CMG)*

A CMG system uses a spinning rotor mounted on gimbals that has a large constant angular momentum. When torque is applied to the gimbals, the spinning rotor causes the spacecraft to precess and thus controls spacecraft pointing. CMG systems can produce large amounts of torque and store large amounts of momentum, compared to the other methods of attitude control.[39]

##### *7.2.3.3.1 Three-Axis Zero Momentum with CMG QTA Evaluation*

Accuracy: 4
Power Requirements: 3
Reliability: 4
*Total*: 11/15

### 7.2.4 Conclusions

Comparing the passive spin stabilization ACS and the active three-axis ACS, the QTA shows the trade-offs between the two in terms of the accuracy, power required, and reliability. Spin stabilization has low power requirements, high reliability, but lower accuracy compared to the three-axis ACS. The three-axis ACS has comparatively higher power requirements, lower reliability, but orders of magnitude higher accuracy. Spin stabilization would help to lower power and risk for a mission that does not require as high accuracy, while a three-axis ACS may be needed for a more detailed mission. However instead of choosing just one of these ACS and sacrificing accuracy or wasting power, what many recent successful interplanetary probes, such as New Horizons and the Microwave Anisotropy Probe (MAP), have employed are multiple types of ACS for different phases of the spacecraft's mission. In this way the spacecraft's performance is optimized for the varied tasks it performs, although the added mass for supporting multiple ACS must be addressed. In terms of just the three-axis system that is used, reaction wheels seem to be the best option since they are very low-mass, and have very high accuracy.

## *7.3 Health Monitoring*

A probe traveling to Gliese 581c will be too far away during most of its mission to be commanded from Earth for critical events, so it will need a highly robust autonomy system to carry out its mission. This involves a robust state machine to help organize the spacecraft's autonomy for correctness, fault detection to determine if something is wrong, and safe modes or other corrective actions for anomalous conditions.

Two missions of interest for their robust autonomous systems are the New Horizons mission to Pluto and the Microwave Anisotropy Probe (MAP). The New Horizons probe is traveling farther than four billion miles from Earth to Pluto and the Kuiper belt, which is more than four light-hours from the sun.[26] The faintness of the sun and the large distance from the Earth makes navigation difficult, and so the autonomous systems onboard New Horizons have features that would be useful for an interstellar probe as well. New Horizons has seven primary modes of operation, employing different ACS, such as passive spin hibernation for the majority of the long journey during which there is little activity to require resources. There are also several three-axis modes including three-axis encounter for precision pointing during the science acquisition part of the mission. Additionally, New Horizons features two safe modes, Earth acquisition and Sun acquisition, which can be triggered by the fault detection autonomy to point the

spacecraft towards the Earth or Sun, respectively, in order to reestablish RF communications with the probe. The onboard fault detection is made robust by specifying nine important parameters for each fault detection rule, including a priority for the rule, processors on which the rule will be evaluated, and a minimum number of samples required before concluding a fault.[26]

Another interesting feature of New Horizons is the ability to autonomously shed non-critical loads to ensure that the power level stays under a preferred maximum of 180W.[26] This feature is complex because the spacecraft must ensure that it does not turn off any critical systems, or interfere with other autonomous behaviors. Autonomous power management will be important for an interstellar spacecraft to be efficient and safe in its use of power and resources.

MAP operates at Lagrange point L2, not nearly as far from the Earth as New Horizons, but far enough to require autonomous capabilities and robust functionality without use of navigation information used by low Earth orbit spacecraft, such as Earth's magnetic field.[24] Like New Horizons, MAP has six different ACS modes, including observing, inertial, sun acquisition, and safehold modes. One mission assurance feature of MAP is having the main operational modes and the safehold mode operate of separate processors. This is a precaution that in case of anomaly on the main processor, operation can be shifted to the safehold mode on the other processor.[24]

# 8 Space Policy

## *8.1 Introduction*

The necessity of international space policies to govern the utilization of the frontier surrounding the earth was discovered shortly after the first successful orbit of an artificial satellite, the U.S.S.R.'s Sputnik in 1957. The United Nations Committee on the Peaceful Uses of Outer Space was formed the next year and has fathered five foundational documents which outline international space policies to this day. Perhaps the most well known and broad reaching document is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies more commonly and concisely referred to as the "Outer Space Treaty[32]." This treaty outlines general principles regarding nuclear technologies in space, the use of celestial territory, national liability for space activities regardless of governmental sponsorship, and contamination. Currently, 98 states have ratified the treaty and an additional 27 have signed their agreement.

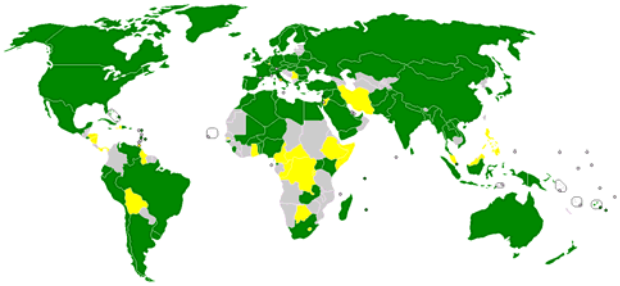

**Figure 27. Map of Ratified (green) and Signed (yellow) States.[32]**

Further documents and principles accepted by the U.N. General Assembly pertain to more detailed specifications for nuclear power sources, the use of satellites for direct television broadcasting, conventions on registering objects launched into space, banning nuclear testing in outer space, remote sensing, and the rescue and return of astronauts to name a few.[32] The documents apply to their specific areas in a broad sense which allows them to remain applicable to the ever-changing technological and

political developments of the abiding countries.

Were an interstellar mission to be launched today, current policies require compliance in several areas: sterilization levels correlating to likelihood of the planet's ability to support or sustain life and the probability of the probe making contact (intentional or otherwise) with its target planet,[5] modifying mission plans in accordance with minimizing risk associated with applied science principles, and formation of failure plans in the case of the mission's use of dangerous technologies capable of large scale damages to earth or LEO. Current policies applied to these areas will be discussed in more detail in the following sections.

## *8.2 Ethical Risks*

The Committee on Space Research (COSPAR) is a leader in the area of concern with biological contamination and spacecraft and continues to formulate and maintain planetary protection policy in this regard. This policy is used as both an international standard and as guidelines for compliance with international agreements.[5]

In Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (also known as the UN Space Treaty of 1967) states:

> States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter, and where necessary, shall adopt appropriate measures for this purpose (UN 1967).[5]

In an interstellar mission of this stature, contamination is an important ethical risk one must take into consideration. There are several different forms of contamination we would need to concern ourselves with. Whether launching fly-by spacecraft, orbiters, probes, landing or penetrating systems, it is necessary to preemptively account for the possibility of a failure at launch, possible alterations of the space environment due to contamination or space debris left behind from the mission. A thorough assessment of potential contamination risks due to any aspect of an interstellar mission needs to be analyzed prior to launch. Of course, it is not possible to keep everything perfectly clean, but measures must be taken to ensure that all possible efforts in sterilization and contamination avoidance are being exercised.

### 8.2.1 Spacecraft Contamination

#### *8.2.1.1 Potential sources*

There are numerous possible sources of contamination in an interstellar mission of this stature. Propellants can be released into the planetary atmosphere, gases generated by chemical reaction, battery electrolytes, organic material degradation under UV lights, gas generated by RTG fission process, and remaining Earth atmospheric gases on spacecraft are also sources.

Metallic based materials such as aluminum, titanium and iron alloys can be found in spacecraft structures. Other metals can be used in battery cells, like nickel and lithium. Tin-lead alloys, copper based alloys and gold and silver used for thermal or protective layers for electronics are also possible sources of contamination[7].

Organic materials can be found in numerous different objects. Polyester/polyamide

materials used in parachutes and airbags, as well as carbon-polyester composites can be used in structures and all pose a possible harmful risk to the space environment. Polyester or polyimide used in thermal covers, polyurethane for coatings or paints, polytetrafluoroethylene for wires and other structural polymers also poses a possible risk.[7]

Silicon based materials are often found in electronic components and optics. Solar cells often include silicon or gallium arsenide. These materials can cause contamination of space.[7]

Radioisotopes, especially plutonium based material, can be a possible source of contamination on an interstellar mission.[7]

Retrorockets which are used in landing procedures can contaminate the ground under and around the lander. There will also probably be changes in the ground properties and pollution due to gas and solid particle emission.[7]

#### *8.2.1.2 Microbial Forward Contamination*

The existence of bacterial spores due to their innate ability to sporulate, can survive in a hostile environment such as that in outer space. This should be of major concern to anyone wanting to conduct an interstellar mission and thus, proper sterilization procedures must be in effect. Incomplete sterilization could lead to contamination of the planet or other celestial bodies.[7]

#### *8.2.1.3 Policy*

The COSPAR Planetary Protection Policy, established in 2002, lays out requirements and controls on contamination for certain space mission/target body combinations. The policy defines five different categories for mission types and the corresponding requirements, with more stringent requirements as the category number increases. Each category pertains to missions "to a target body of chemical evolution and/or origin of life interest for which scientific opinion provides a significant chance of contamination which could jeopardize future biological experiments." Categories III and IV are the only two that pertain to the type of interstellar missions this paper is concerned with.[5]

Category III pertains to flyby and orbiter missions. Requirements for missions of this type would include documentation (more so than was required for a Category II), trajectory biasing, use of cleanrooms during spacecraft assembly and testing, and possibly bioburden reduction.[5]

Category IV pertains to probe and lander missions. Requirements for missions of this type would include more detailed documentation than was necessary for Category III, a probability of contamination analysis, an inventory of most of the constituent organics of the mission, and increasing the amount of implementing procedures. The implementing procedures can include trajectory biasing, use of cleanrooms, bioload reduction, possible partial sterilization of the direct contact hardware and a bioshield for that hardware. In general, the requirements are like those of *Viking*, except for complete lander/probe sterilization.[5]

The COSPAR Planetary Protection Policy contains the existing source for reports that need to be submitted within a reasonable time, not to exceed six months after launch, about the procedures and computations used for planetary protection in that particular mission. Reports must be filed again within one year after the end of a solar-system

exploration mission regarding the target(s) that may have been exposed to contamination.

### 8.2.2 Nuclear Contamination

Another area of concern in an interstellar mission, if nuclear materials were used in the design, would be with regard to nuclear contamination. Different measures would need to be taken depending on the amount and type of nuclear matter used for the power or propulsion source.

A pre-launch vehicle breakup analysis should be completed in case any failure during launch occurred or an accidental Earth reentry. It should thoroughly evaluate aerospace nuclear safety and prepare for launch contingency plans.[21]

A rapid response effort would need to be designed for any possible launch failure. Policy should be drawn up prior so as to illustrate requirements regarding this effort and responsible parties.

Two other areas of concern regarding nuclear contamination is the contamination of the space environment and space debris. If a catastrophic failure of the spacecraft occurred, worry of contamination to other celestial bodies in the area should be of concern. Similarly, space debris also is not healthy for the space environment. It could result in the costly endangerment of future missions or other objects currently in space.

Interstellar missions will continue to require rigorous sterilization procedures. Standards recommended by current policy are sufficient and applicable for current technologies. Future policy may need to be developed as necessary in regard to the specific design of the mission and spacecraft.

## *8.3 Mission Assurance Issues*

Space exploration is an exciting and rewarding venture, and is correspondingly associated with high levels of risk. In planning for mission success, we must consider concerns for safety and liability in many areas. The previous sections of background research into the relevant space policy for an interstellar mission show that the areas of highest risk for an interstellar mission are most likely spacecraft contamination and the use of nuclear devices.

Another area of risk to be briefly mentioned is the responsibility assumed when launching a spacecraft. As in any mission, a State is responsible for any consequences of launching a spacecraft. The State launching the spacecraft is liable for any damage caused by launched materials on the ground or in the air, with no need for proving fault or negligence, only causality. Launch liability is highly risky because legal treaties state unlimited compensation for damage incurred from space accidents.[4]

## *8.4 Conclusions*

Due to the far reaching nature of current international space policies, many different mission types and contingencies relevant to interstellar missions fall within the existing regulations. The general purposes of these regulations are to protect the earth against back contamination from return missions, to protect the citizens and property on earth from large scale failures by any country, and to protect the integrity of celestial bodies for future missions.

Current policy falls short on several terms including applicability to potentially dangerous power sources besides nuclear fission. Interstellar missions would likely require specific procedures in order to

ensure that their power and propulsion systems do not endanger the earth during their earth departure stage and possibly may even need to be activated outside of low earth orbit. Article XXI of the Convention on International Liability for Damage Caused by Space Objects states that:

> If the damage caused by a space object presents a large-scale danger to human life or seriously interferes with the living conditions of the population or the functioning of vital centres, the States Parties, and in particular the launching State, shall examine the possibility of rendering appropriate and rapid assistance to the State which has suffered the damage, when it so requests. However, nothing in this article shall affect the rights or obligations of the States Parties under this Convention.[32]

In order to provide assistance for large-scale damages from technologies which are much more potent that nuclear fission, such as fusion and antimatter, the aforementioned article may not be sufficient to prevent further loss of life and property after initial damages have occurred. International organizations dedicated to quick large scale responses that are supported on a global scale may be necessary.

Current contamination standards may be sufficient to protect the earth from back-contamination, but once lunar outposts are established it may be possible to use the base effectively as a quarantine of interstellar materials. The returning specimens could be examined utilizing the scientific equipment of the outposts before bringing them to Earth.

The majority of policies outlined by the United Nations remains applicable when examined in context of interstellar missions, however as technology continues to evolve policies will require updating to remain relevant.

# 9 Results and Conclusions

The interstellar mission design process will likely be held in stasis while technology catches up with man's desire to expand beyond the solar system. Even though an international collaborative effort of research would likely last several hundred years before fruitful results are achieved, the practice of working in a single unified direction will always benefit those involved.

In order to pursue the scientific objectives relevant to an interstellar earth like planet, instrument systems should be designed with similar specifications as the SWAP and UVIS packages. Efficient expenditure of mass and power with a design focused around reliability should occupy the main physical requirements of any instrument package. The two instruments selected by the applied QTA span several of the science goals deemed most important in this study without compromising the probe's power and mass limitations.

Propulsion systems suggested for further development by this document include fusion and light sale systems. Fusion propulsion systems require significantly more development than light sails, however the technology to efficiently manufacture, launch, and construct light sail systems of the magnitude required by an interstellar mission will not be available without much continued research.

One of the two main factors that determine whether or not a mission to another solar system lies within technological capabilities is the ability to produce enough power to operate the spacecraft. The power system analysis suggested two areas of greatest potential for interstellar applicability; fusion power and radioisotope power. Fusion power systems are still within the realm of

science fiction for what looks to be a scale of centuries. Once the fundamental processes are able to be utilized on larger designs, these systems must be made mass efficient in order to be useful to interstellar travel. Radioisotope power systems have been proven and flown on previous NASA missions within and eventually beyond the edge of this solar system. However, for interstellar travel durations on the order of centuries these power sources will likely require significant redesign to account for the extended power requirements. It may also require very large scale manufacturing of plutonium to power the probe, something that has been disbanded because of its devastating potential as a weapon component.

The passive spin stabilization ACS and active three-axis ACS will likely both need to be implemented in order to conserve the maximum amount of mass and power during the transit of interstellar space. The trade-offs of using solely one system are complemented by the other when both are applied to their most relevant mission segments. Reaction wheels were suggested by this analysis for their low mass and high sensitivity.

Policies for interstellar missions will be most dependent on the technologies being applied and the public's opinions of them. For potentially dangerous power and propulsion sources such as antimatter and fusion, specific international regulation would likely need to be developed. Drafting such policies will only be possible after the control and usage mechanisms are understood. Contamination policies currently in existence could be readily applied to an interstellar mission but perhaps with higher rigors due to the greater consequences of forward contamination. The time delay involved in sending a follow-up mission may be so great that the effects of any forward contamination on an interstellar planet may be extremely widespread before they are detected.

The technologies and components discussed in this analysis all require significant research and adaptation before being ready for application in interstellar travel. Mass and power efficiency and longevity will be the most significant areas of development for existing technologies in order to lessen their effect on the mission duration. An interstellar probe mission to an earth-like planet could yield vast amounts of technological advancement and scientific achievement that would benefit science and humanity for many generations to come.

# 10 Acknowledgements

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# 11 Appendices

## *11.1 Propulsion System QTA*

Total Score = ( 0.6(Isp + mass + reliability) + 0.4( (cost to develop + cost to implement)/2 + time to develop + mission time + safety) / 17 ) * 5

Will it physically work? (60% total, 20% each)

### 11.1.1 ISP

- 1. under 1,000 seconds
- 2. 1,000 – 1,000,000 seconds
- 3. 1,000,000 – 10,000,000 seconds
- 4. over 10,000,000 seconds, but not infinite
- 5. infinite

### 11.1.2 Mass

- 1. a billion or more kilograms (the mass of the population of Texas)
- 2. millions of kilograms
- 3. hundreds of thousands of kilograms (the ISS's weight)
- 4. thousands of kilograms
- 5. hundreds of kilograms or less (Voyager 1's weight)

### 11.1.3 Reliability

- 1. The design is very complicated and may have many moving parts. It has a poor performance history or very uncertain reliability due to lack of technology.
- 2. The design may is complicated and most likely contains moving parts. The technology has been proven theoretically but its reliability is uncertain due to lack of implementation.
- 3. The design may be complicated and may involve moving parts. Good potential for robust performance. The technology shows promising development, though applications outside the lab may be limited.
- 4. Mostly simple design. May have moving parts, but they aren't a high risk. The technology has been proven, but our experience with it is limited.
- 5. Design is simple, with no or negligible moving parts. Uses technology with which we have extensive experience. Has excellent performance history or prospective technology.

### 11.1.4 Cost to develop

Will people be willing to do it? (40% total, 20% each)

Total Cost (an average of the two sub-categories)

- 1. unrealistically huge commitment of global resources
- 2. The government would need to commit a disproportionate amount of the national budget to it
- 3. NASA would need more money from the government
- 4. reasonable under current budget if NASA really focuses on it
- 5. totally reasonable under the current NASA budget for the average existing research project

### 11.1.5 Cost to implement

- 1. unrealistically huge commitment of global resources
- 2. The government would need to commit a disproportionate amount of the national budget to it
- 3. NASA would need more money from the government
- 4. reasonable under the current budget if NASA really focuses on it
- 5. totally reasonable under the current NASA budget for existing probe missions

### 11.1.6 Time to develop

- 1. in the unforeseeable future
- 2. > 100 years
- 3. 50-100 years
- 4. 10-50 years
- 5. < 10 years

### 11.1.7 Mission time

- 1. thousands of years or more
- 2. 300-1,000
- 3. 200-300
- 4. 75-200
- 5. 75 years or less

### 11.1.8 Safety

- 1. there is no theoretically proven way to make it pass existing safety regulations
- 2. The way to make it pass existing safety regulations is only theoretical
- 3. can be made to pass existing safety regulations with some additional technology that is feasible but not yet in use
- 4. can be made to pass existing safety regulations with some additional, existing technology
- 5. easily passes existing safety regulations without any significant part of the design devoted to safety

## *11.2 Power System QTA*

Total Score = ( 0.6(specific energy + lifetime + reliability) + 0.4( (cost to develop + cost to implement)/2 + time to develop) / 13 ) * 5

Will it physically work? (60% total, 20% each)

### 11.2.1 Power output per mass (specific energy, kW-h/kg)

- 1. specific energy <= 0.1
- 2. specific energy <= 10
- 3. specific energy <= 1 000
- 4. specific energy <= 100 000
- 5. specific energy > 100 000

### 11.2.2 Lifetime

- 1. 75 years or less (significant support)
- 2. 75-200 years (your grandchild could see it)
- 3. 200-300 years
- 4. 300-1,000 years
- 5. thousands of years or more

### 11.2.3 Reliability

- 1. The design is very complicated and may have many moving parts. It has a poor performance history or very uncertain reliability due to lack of technology.
- 2. The design may is complicated and most likely contains moving parts. The technology has been proven theoretically but its reliability is uncertain due to lack of implementation.

- 3. The design may be complicated and may involve moving parts. Good potential for robust performance. The technology shows promising development, though applications outside the lab may be limited.
- 4. Mostly simple design. May have moving parts, but they aren't a high risk. The technology has been proven, but our experience with it is limited.
- 5. Design is simple, with no or negligible moving parts. Uses technology with which we have extensive experience. Has excellent performance history or prospective technology.

### 11.2.4 Time to development

Will people be willing to do it? (40% total, 20% each)

- 1. in the unforeseeable future
- 2. centuries
- 3. 50-100 years
- 4. 10-50 years
- 5. less than 10 years

### 11.2.5 Cost to develop

Total Cost (an average of the two sub-categories)

- 1. unrealistically huge commitment of global resources
- 2. The government would need to commit a disproportionate amount of the national budget to it
- 3. NASA would need more money from the government
- 4. reasonable under current budget if NASA really focuses on it
- 5. totally reasonable under the current NASA budget for the average existing research project

### 11.2.6 Cost to implement

- 1. unrealistically huge commitment of global resources
- 2. The government would need to commit a disproportionate amount of the national budget to it
- 3. NASA would need more money from the government
- 4. reasonable under the current budget if NASA really focuses on it
- 5. totally reasonable under the current NASA budget for existing probe missions

## *11.3 Autonomous Systems QTA*

### 11.3.1 Attitude Control System (ACS)

#### 11.3.1.1 Accuracy

- 1. Coarser than ± 1°
- 2. ± 0.1° to ± 1°[6]
- 3. ± 0.01° to ± 0.1°
- 4. ± 0.001° to ± 0.01°
- 5. Finer than ± 0.001°

#### 11.3.1.2 System Power Requirements (taken from New Horizons model)[11]

- 1. >180W
- 2. 170-180W
- 3. 160-170W
- 4. 150-160W
- 5. <150W

#### 11.3.1.3 Reliability

- 1. The setup is very complicated and may have many moving parts, or the technology has not even been proven to work
- 2. The setup may be complicated and contain several moving parts, and/or the technology has been proven theoretically but never implemented
- 3. The setup may be somewhat complicated and contain several moving parts. Or, the technology may have been tested in the lab, but applications outside the lab have been very limited.
- 4. Some moving parts, mostly simple setup, the technology has been proven and used, or our experience with it is limited
- 5. No or negligible moving parts, extremely simple setup, or a proven technology that we have extensive experience with

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