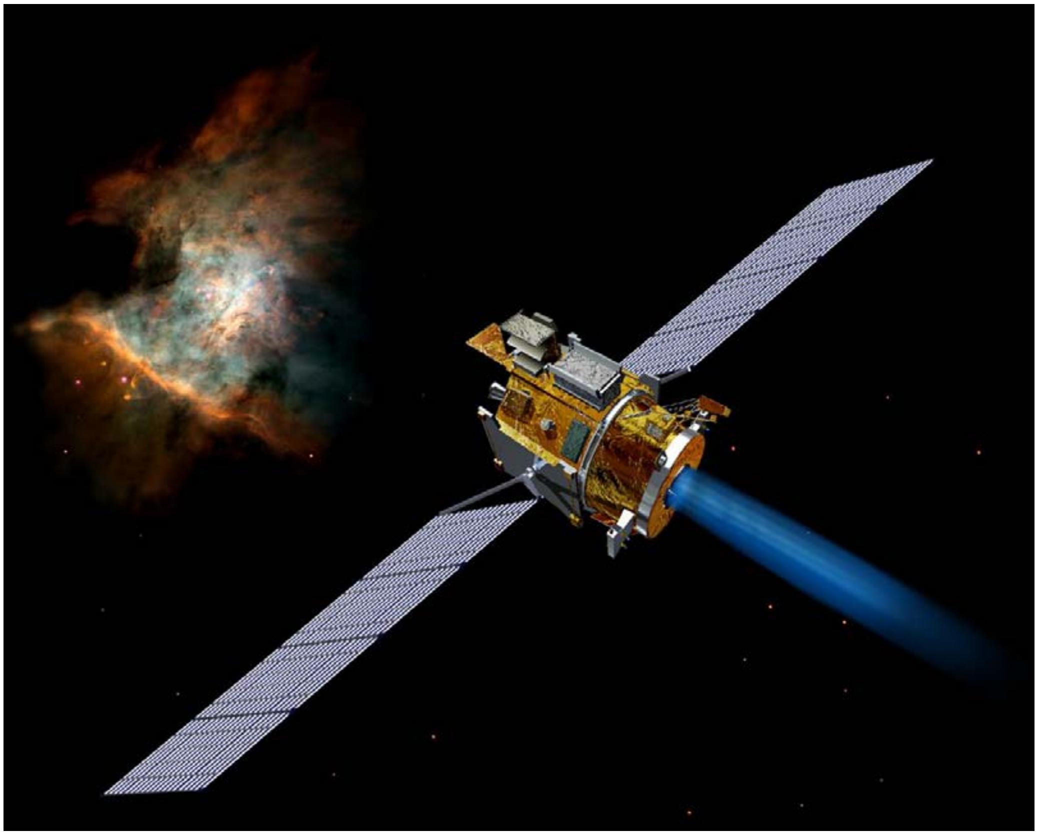
A SunCam online continuing education course

Spacecraft Subsystems Part 4 – Fundamentals of Propulsion



by

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1. Introduction

Spacecraft are man-made machines that operate in space. An earth orbiting spacecraft is normally referred to as a satellite, although it is manmade (aka "artificial") as opposed to a natural satellite like our moon. A spacecraft is typically subdivided into two major parts, the payload and the bus. Where the mission can be defined as the purpose of the spacecraft and is usually identified as the payload part of the spacecraft (e.g. scientific instruments, communications). The propulsion subsystem and other subsystems (e.g. attitude control, electrical power, thermal control) are part of the bus. With the primary goal of achieving a successful mission, most bus design constraints focus on maximizing the effectiveness of its payload [ref. 1].

Propulsion in the context of this course refers to the ability of a spacecraft to maintain its correct satellite orbit or maintain its flight path's course and speed for deep space navigation. This is the job of the spacecraft's propulsion subsystem, essential to successfully performing their mission. This subsystem generates a force that is typically measured in newtons (N) or in pounds of force (lbf). To achieve this, many propulsion methods can be employed.

Note: All figures in this course have no scale.

Because of their flight experience and common use, liquid hydrazine and ion (aka electrostatic) propulsion will be described in more detail in this course; with each propulsion method briefly described as follows:

- **Solid** - identified as a motor, mostly used for launch, fuel and oxidizer are combined in a solid block that once started, does not stop until the chemical reaction is completed
- **Liquid** - identified as an engine, these are used for launch and in space, liquid fuel and oxidizer (or catalyst) are combined, can be controlled (e.g. started/stopped).
- **Hybrid** - employs combination of solid and liquid, typically with the solid as fuel and liquid as the oxidizer
- **Electrothermal** - fuel is heated electrically and then expanded thermodynamically to supersonic speeds
- **Ion (aka Electrostatic)** - ions are accelerated through an electrostatic field.
- **Electromagnetic** - ions and electrons are accelerated in a plasma using electrical and magnetic fields
- **Nuclear** - using plutonium or uranium fuel to either create heat to expand a gas through a nozzle or produce electricity to power an electronic thruster
- **Solar Sailing** - uses large spacecraft appendages (e.g. solar arrays) to reflect solar energy

Orbit Types

A satellite's operating environment largely depends on its orbit type, which is primarily driven by its intended mission. The three common earth orbiting satellite types are geosynchronous orbit (GEO), highly elliptical orbit (HEO), and low earth orbit (LEO) as seen in the following figure [ref. 1].

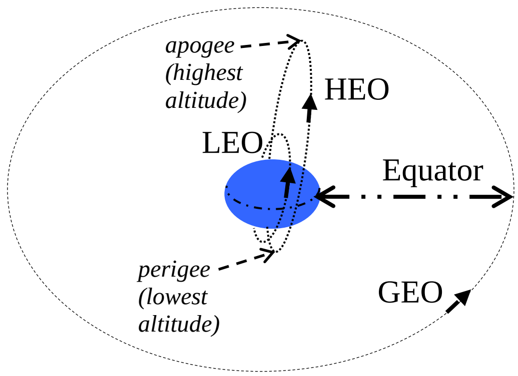

Figure 1.1: Common Earth Orbit Types
[Reprint from source: ref. 1]

LEO satellites have an altitude of less than one thousand miles. Satellites in HEO can have a wide ranges of altitudes for perigee (lowest altitude) to apogee (highest altitude).

GEO satellites, orbiting about the equator at some small angle (inclination angle), have an altitude of ≈ 23,000 miles above earth. At this altitude, satellites have the same period of rotation as the earth, appearing fixed relative to earth. Because of this, these satellites are most commonly used for communications purposes (e.g. television) since there is no need for the receive dish on earth to track the satellite [ref. 1].

Perturbing Forces

Once in its correct orbit, satellites are susceptible to external forces acting against it, referred to a perturbing forces, which can affect its orbital parameters (e.g. apogee, perigee). The dominant perturbing forces acting against LEO satellites is the earth's atmospheric drag. This in effect applies a braking effect on the satellite which lowers its apogee and perigee. Even LEO satellites have apogee and perigee, however, they are much more circular (i.e. closer in altitude) than in HEO satellites. The primary perturbing forces acting against GEO satellites are gravitational pulling forces from the sun and the moon. HEO satellites can experience these gravitational forces and also the earth's atmospheric drag, depending on its apogee and perigee respectively.

A satellite's propulsion subsystem is used to counter these perturbing forces, performing periodic maneuvers as needed to maintain its proper earth orbit. These maneuvers are known as stationkeeping maneuvers. Subsequently, because LEO satellites are most susceptible to orbital decay, which can be defined as a satellite's overall decrease of its orbital altitudes (perigee and apogee), its propulsion subsystem prevents them from reentering and burning up in the earth's atmosphere.

For deep space navigation, the dominant perturbing forces acting against spacecraft are solar gravitational and also will occur during flybys of other bodies (e.g. planets, asteroids, comets). To counter these forces and keep the spacecraft in its correct flight path, the propulsion system will fire to correct its velocity vector's magnitude and/or direction.

Apollo 13

Propulsion systems have been successfully utilized as intended to provide satellite stationkeeping and deep space navigation. They have also been used to provide backup up when needed. One well known example of this is in the Apollo 13 mission, April 11-17, 1970). In order to save the astronauts after an explosion caused a mission abort, the lunar module's propulsion system which was designed for landing on the moon, was used instead to return the astronauts safely to earth. The following figure is an artist's rendition of Apollo 10, firing its descent stage engine for lunar landing.

Figure 1.2: Apollo 10's Lunar Landing - Artist's Rendering
[Reprint from source: NASA @ nasa.gov]

The following figure depicts a photo taken from the command service module, of Apollo 11's lunar module Eagle in a landing configuration, with the stages and descent engine identified. The descent stage was left on the moon and served as a launch pad for the ascent stage to return the astronauts to the command service module. The ascent stage was left in orbit around the moon where it eventually decayed and crashed into it.

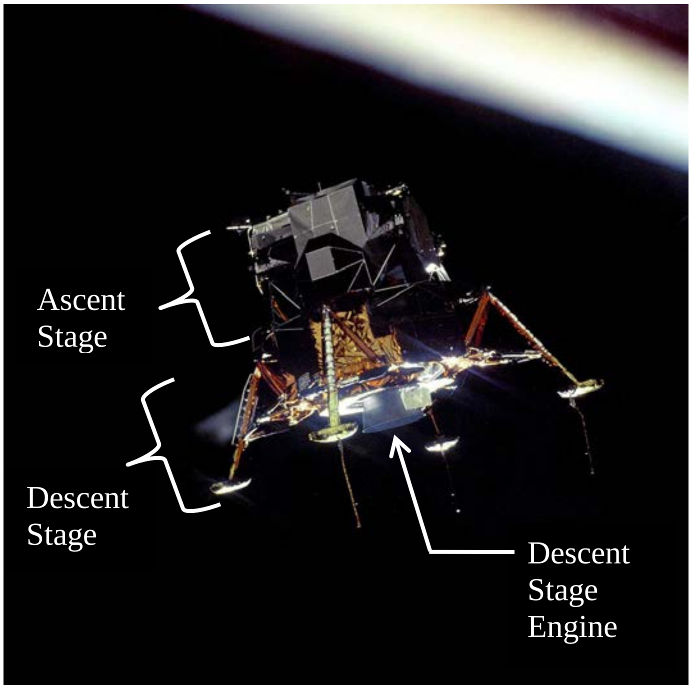

Figure 1.3: Apollo Lunar Module Stages
[Reprint from source: NASA @ nasa.gov]

The lunar module descent propulsion system (DPS) components were:

- Engine:
  - propellant control valves
  - injector assembly
  - combustion chamber
- Hypergolic propellants: Two liquid chemicals that combust on contact, therefore, there is no need for a spark plug igniter.
  - 2 fuel tanks of aerozine -50: half unsymmetrical dimethylhydrazine and half hydrazine.
  - 2 oxidizer tanks of dinitrogen tetroxide (N_2O_4), commonly referred to as nitrogen tetroxide or its abbreviation NTO.
- Helium tank for pressurization

The following figure is a detail of the lunar module descent stage identifying major components.

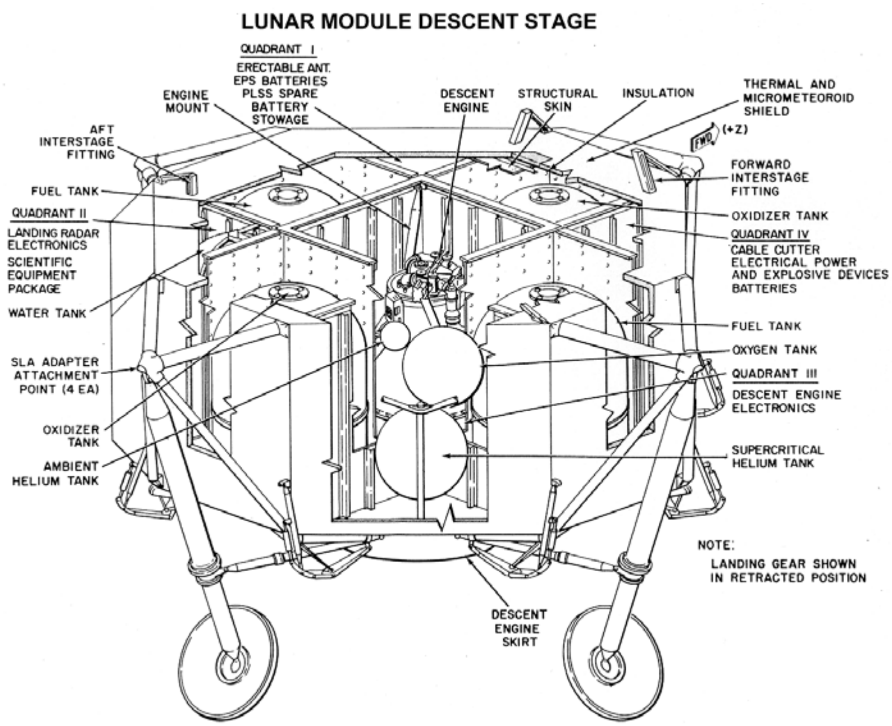

Figure 1.4: Apollo Lunar Module Descent Stage Detail
[Reprint from source: NASA @ nasa.gov]

The following figure is a photo showing the underside of a lunar module (LM) descent stage and the four hypergolic fuel tanks – 2 fuel and 2 oxidizer.

Figure 1.5: Apollo Lunar Module Descent Stage - Underside
[Reprint from source: NASA @ nasa.gov]

The following is a portion of the Apollo 13 events timeline showing the use of its lunar module descent engine, 14-16 April 1970.

Table 1.1: Apollo 13 Lunar Module (LM) Descent Propulsion System (DPS) Ignition

Date/Time (GMT)	DPS Event
14 April, 08:42:43	Midcourse correction ignition to free-return trajectory
14 April, 08:43:17	Midcourse correction cutoff
15 April, 02:40:39	Transearth injection ignition*
15 April, 02:45:02	Transearth injection cutoff
16 April, 04:31:28	Midcourse correction ignition
16 April, 04:31:42	Midcourse correction cutoff

*Note: About 2hrs after "slingshotting" around moon.

Apollo 13 began its return to earth in the following "docked" configuration (shown with astronaut to provide scale). The lunar module was jettisoned when it was no longer needed, at 16:43:00 on April 17th, only about one hour prior to command module reentry into earth's atmosphere.

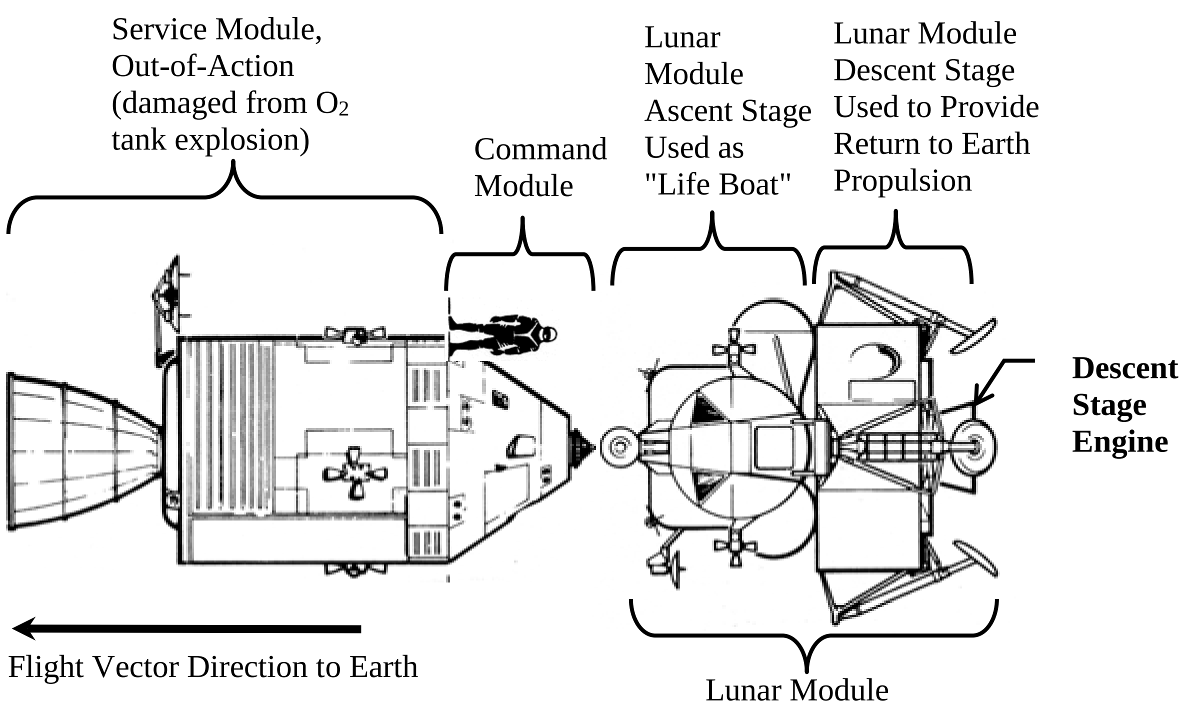

Figure 1.6: Apollo 13 Return Configuration
[Partial reprint from source: NASA @ nasa.gov]

2. Liquid Hydrazine Propulsion

Hydrazine is unique in that it can be used in either of the two liquid propellant types – mono or bi. Hydrazine is a chemical compound which provide spacecraft thrust forces as a result of its chemical reaction. When used as a monopropellant, a decomposition reaction produces a large volume of hot gas from a small volume of liquid hydrazine that uses a catalyst to ignite and speed up the reaction. This reaction is exothermic (releasing energy) that can be characterized by the following chemical equation:

$N_2H_4 \rightarrow N_2 + 2H_2$

Where N_2H_4 is hydrazine (the reactant) in a liquid state and is the molecular formula showing the total number of atoms of each element (2-nitrogen and 4-hydrogen) in one molecule of the compound. $N_2 + 2H_2$ represents the resulting chemicals produced to provide the thrust force vector as depicted in the following figure.

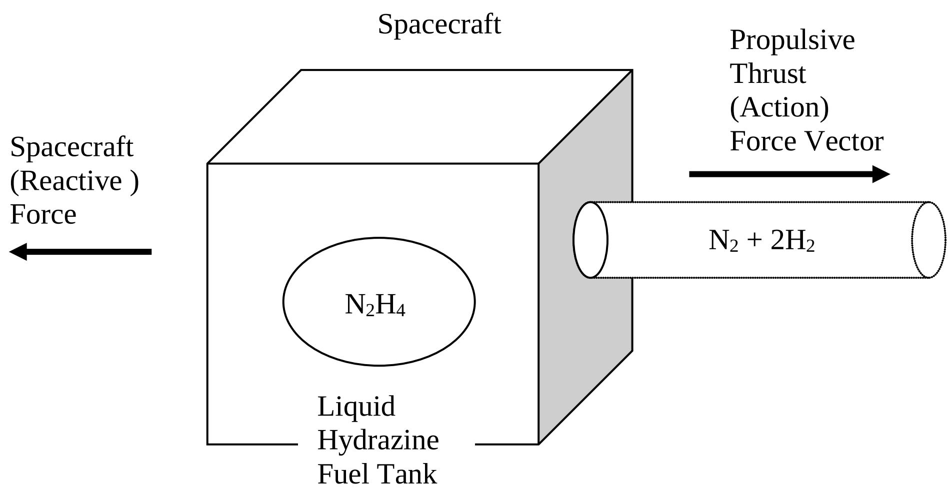

Figure 2.1: Hydrazine Decomposition Reaction

Liquid hydrazine is used in the following three compounds:

- hydrazine (N_2H_4)
- monomethylhydrazine (MMH, CH_3NHNH_2)
- unsymmetrical dimethylhydrazine (UDMH, $(CH_3)NNH_2$)

UDMH and MMH have better (greater) operating temperature ranges than hydrazine.

When used with a catalyst or heated, the liquid hydrazine fuel reacts exothermically, igniting a decomposition chemical reaction that is classified as a monopropellant. When igniting the reaction after combining in the combustion chamber with a separately stored liquid oxidizer, the liquid propulsion system is classified as a bipropellant. This is the same classification concept for all other liquid propellants too.

Space Shuttle

Because of flight experience (e.g. Apollo), a bipropellant NTO/hydrazine-based system was also used for the space shuttle's (1981-2011) two orbital maneuvering system (OMS) engines. Using MMH as the fuel, these were pressure-fed by helium that provided the following functions:

- orbit insertion
- orbit transfer
- rendezvous
- deorbit
- orbit abort

The reaction resulting from this bipropellant combination can be expressed by the following chemical equation:

$4CH_3NHNH_2 + 5N_2O_4 \rightarrow 9N_2 + 4CO_2 + 12H_2O$

The following is a photo of the space shuttle Discovery's aft engines, showing the two OMS engines; note, there were two for redundancy. Also, you cannot miss the three massive nozzles of the main engines which were used to provide the necessary launch thrust. Burning for about 8.5 minutes after liftoff, the main engines were also liquid bipropellant, using hydrogen and oxygen. Amazingly, no engines were used in landing the orbiters, as that was the only purpose of the wings. Where a D-wing (aka delta wing) design was needed to provide enough lift to glide the orbiter to its landing site.

Figure 2.2: Space Shuttle OMS
[Reprint from source: NASA @ nasa.gov]

Functional Concept

Hydrazine liquid rocket engines consist of the following components:

- propellant fuel – one of the three forms of hydrazine
- pressure fed flow control system: inert gas tank, piping, control valves, regulators
- injector
- igniter: catalyst (monopropellant) or hypergolic oxidizer (bipropellant)
- thrust chamber: combustion chamber, exhaust nozzle, cooling
- thrust control

The pressure fed flow control system forces the propellant(s), under inert gas pressure (e.g. helium), through an injector which vaporizes the propellant for uniform and efficient burning upon entering the thrust chamber where combustion occurs. The chemical product is accelerated and expanded out of the exhaust nozzle to provide thrust force. Controlling the thrust vector direction is commonly achieved by gimbaling the thrust nozzle.

For monopropellant systems, a catalytic bed of iridium is preferred because it begins the chemical decomposition process with hydrazine on contact at room temperature. For bipropellant systems, since NTO is hypergolic with hydrazine, it is commonly used as the oxidizer, which ignite on contact after combining in the combustion chamber.

Cassini Spacecraft

Another example of a bipropellant liquid hydrazine propulsion system, also using NTO/MMH, was in the Cassini spacecraft (1997-2017), shown in the following figure. Where one engine provided speed and course corrections throughout its mission. The other engine was a backup in case of a primary engine failure.

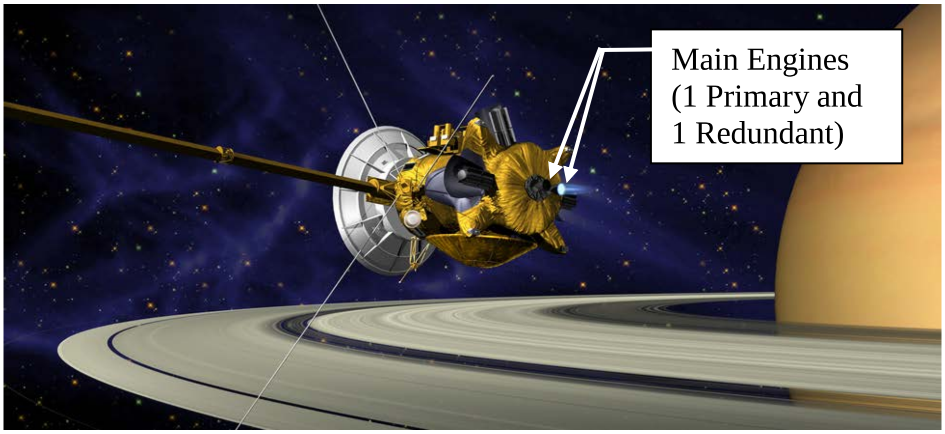

Figure 2.3: Cassini Spacecraft Main Engines, Artist's Rendering
[Reprint from source: NASA @ nasa.gov]

3. Ion Propulsion

Ion propulsion (aka electrostatic) accelerates ions using a high voltage electrostatic field to speeds up to 90,000 mph to produce an ion thrust beam. The ionization process creates a plasma which consist of positively charged ions and negatively charged electrons. The ions are used to provide the propulsive force because of their extremely large mass compared to electrons. For effective and efficient thrust, gases with high molecular masses are needed (e.g. xenon, mercury, cesium, krypton, and argon) as the fuel propellant.

Ion propulsion has a much higher specific impulse (≈ 3x minimum) compared to liquid hydrazine chemical propulsion. Specific impulse is defined as the total impulse per unit weight of propellant used measured in seconds (i.e. thrust force to propellant mass consumed). Because of this, ion propulsion could be a good choice for spacecraft missions needing to save mass of stored fuel. Ion propulsion has been successful in GEO satellites as well as interplanetary missions.

Deep Space 1

A good example of ion propulsion is the Deep Space 1 (1998-2001). This spacecraft traveled over 163 million miles on an interplanetary mission, primarily to test new spacecraft technologies (e.g. ion propulsion), but it also explored asteroid 9969 Braille and comet Borrelly. This spacecraft, depicted in the following figure showing the ion beam produced by its 30cm diameter thruster, employed the NSTAR (NASA Solar Technology Application Readiness) xenon thruster ion propulsion system.

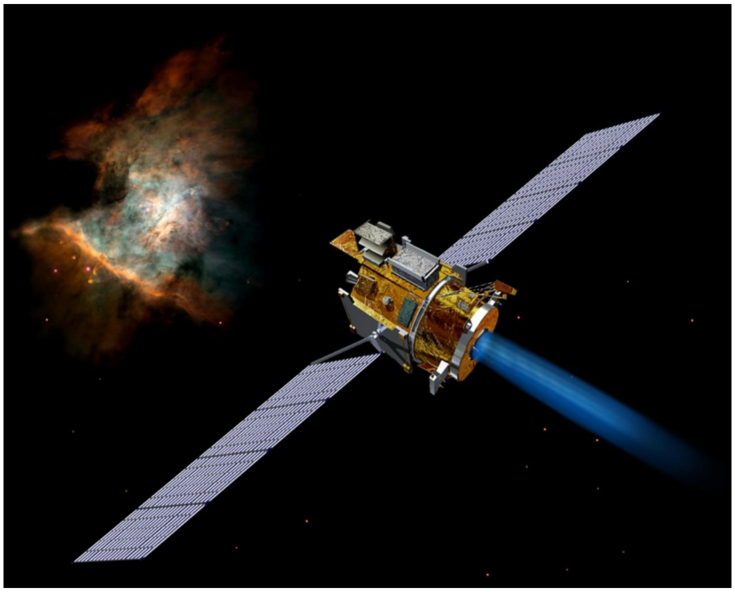

Figure 3.1: Deep Space I
[Reprint from source: NASA @ nasa.gov]

Functional Concept

In ion propulsion, a gas propellant becomes ionized producing a plasma. Plasma consists of positive (+) ions and negative (-) electrons with an overall charge of zero; similar to a gas but is affected by electrical and magnetic fields, and therefore is sometimes referred to as the 4th state of matter (i.e. solid, liquid, gas, plasma). A common example of a naturally occurring plasma is lightning. In order to create a plasma, the fuel's electrons must be separated from its protons and neutrons. This separation can be achieved using any one of the following methods, where the electron bombardment is most common:

- electron bombardment using high energy negatively charged electrons
- radio frequency (RF) excitation using high frequency (HF) electromagnetic fields
- pulsed inductive excitation - current pulses from capacitors create an electromagnetic field
- electron-cyclotron resonance (ECR) using microwave electromagnetic radiation

The most common propellant gas used for ion propulsion is xenon (Xe). This gas is effective due to its high atomic mass and it also has a high storage density. In addition, because it is a noble gas element, it can be safely stored on a spacecraft. The components used for the production of ion propulsion using xenon are:

- xenon gas propellant
- ionization chamber
- ion thruster that includes screen and accelerator grids located in aft part of thruster; where the electrostatic fields between grids have a large voltage gradient, 1-10kV.
- power supply for creating the voltages and currents needed
- propellant management to reduce high pressure stored propellant to a controlled lower pressure
- performance control and monitoring

Using these components and the electron bombardment method to separate the xenon's electrons, the following sequence of events are needed to produce an ion thrust beam:

1. Electrons generated by thermionic emission using hollow discharge cathode
2. Electrons are attracted to the discharge chamber's high positively charged wall
3. Electrons and xenon gas (at low pressure) propellant enters ionization chamber
4. Electrons bombard xenon gas atoms in ionization chamber, separating the atom's electrons
5. Xenon gas propellant becomes ionized producing a plasma, its electrons have been separated
6. Plasma is contained using a magnetic field
7. Ions (in the plasma) move towards aft grids that contain thousands of precisely aligned holes
8. Ions pass through the screen grid, a positively charged electrode with a high voltage
9. Ions are accelerated towards the accelerator grid, a negatively charged electrode.
10. Accelerated ions (+) form an ion beam to provide the thrust force and the separated electrons (-) are expelled in equal amounts to ensure the overall process remains neutral

Besides producing the ion thrust beam, the final sequence of expelling electrons is also a very important one. This is because maintaining an imbalance (i.e. more electrons than ions) would give the spacecraft a negative charge. This imbalance could cause undesired forces to interact with the ion propellant, drawing ions back into the spacecraft and therefore reducing thrust. It can also cause surface erosion.

Hall Current Thrusters

Another common technology used to accelerate ions is Hall current (aka Hall-effect) thrusters. Named after its discoverer Dr. Edwin Hall (1855-1938). This technology also uses electron bombardment as previously described. But instead of grids, orthogonal electric and magnetic fields are used to create a current (electron flow) that interacts with the magnetic field, which accelerates ions by force in the axial direction. This ionization process can be described by the following chemical equation using xenon gas:

$e^- + Xe^0 \rightarrow Xe^+ + 2e^-$

AEHF-1

Ion propulsion, using Hall current thrusters, also proved to be a viable backup to help save a military communications satellite. Soon after liftoff of the first advanced extremely high frequency (AEHF-1) satellite on August 14, 2010, the hydrazine fueled liquid apogee engine (LAE) failed to fire due to a propellant line blockage. Other propulsion systems were needed to perform the orbit raising function to boost AEHF-1 to its operational GEO orbit.

Figure 3.2: AEHF-1
[Reprint from source: af.mil]

A four phased plan was devised and successfully implemented to use its much smaller propulsion systems. Phases 1 and 2 were needed to raise AEHF-1's orbit to avoid immediate threats from the earth's atmospheric drag and the orbiting "mine field" of space debris as depicted in the following figure. To achieve this task, the hydrazine-based reaction engine assembly (REA) thrusters, designed for attitude control (i.e. stabilization), were fired during these first two phases.

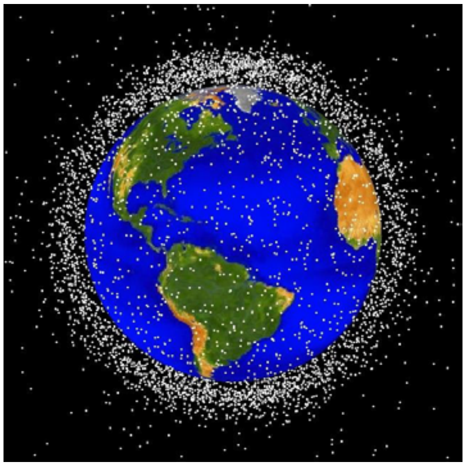

Figure 3.3: Space Debris
[Reprint from source: NASA @ nasa.gov]

Phases 3 and 4 featured the hall current thrusters (HCTs), designed primarily for stationkeeping, completed this unique orbit raising plan. The major events and the four phases are summarized in the following table. Another remarkable achievement, because of the conservative and efficient use of the REA and HCT propulsion systems, no adverse impacts to mission longevity are anticipated. AEHF-1 is still expected to reach its planned 14 year mission life.

Table 3.1: AEHF-1 Orbit Raising Summary

Phase	Operation/Event	Completion Date	Perigee	Apogee
0	Space injection	Aug. 14, 2010	140 mi	31,000 mi
0	LAE ignition attempt 1 failed	Aug. 15, 2010	140 mi	31,000 mi
0	LAE ignition attempt 2 failed	Aug. 17, 2010	140 mi	31,000 mi
1 & 2	REA burns succeeded	Sept. 22, 2010	3,000 mi	31,000 mi
3	HCT activations succeeded	June 2, 2011	17,000 mi	32,000 mi
4	HCT activations succeeded	Oct. 24, 2011	22,300 mi	22,300 mi

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Note: If there was no date on a sourced website article, the year the article was accessed was used.