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Attached you will find the Final Report for the Cooperative Agreement NNC04GA81G. This will complete the close-out requirements accordingly to NASA policy.

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Outer planetary exploration spacecraft have relied on Radioisotope Power Systems (RPS) to provide power. This is necessary as solar power is not useful beyond the inner planets. For propulsion these spacecraft have made use of chemical systems. A study was undertaken to look at the possibility of designing a spacecraft for outer planetary exploration that would use an RPS in combination with Electric Propulsion. That is, the RPS would be the sole power provider to the EP system. Recent improvements in RPS's have made Radioisotope Electric Propulsion (REP) more of a possibility.

The combined power and propulsion technologies of REP and a direct trajectory would potentially enable a new class of missions - high delta V, beyond Mars orbit for a small spacecraft primarily suited for small body capture (orbit capture or co-orbit). A study was undertaken to evaluate the feasibility of a REP spacecraft for a selected representative mission of this type. To evaluate the potential of these technologies, a design reference mission was established and a conceptual design of a spacecraft developed. The following paper describes the Ion Propulsion System, one particular subsystem onboard of the spacecraft.

In order to have a successful mission, the Ion Propulsion System (IPS) is expected to provide several capabilities. It must provide a total velocity change of approximately 9 km/sec to the spacecraft. The IPS will provide pitch and yaw control for the spacecraft while the Ion engine is in operation. The two thrusters are mounted onto a common platform that is attached to a 2-axis gimbal. Pulsed Plasma thrusters control the roll axis of the spacecraft. The IPS will have to last for a total mission duration of approximately 6 years (60,000 hours). The current ion thruster record holder was operated continuously for approximately 30,000 hours. It is expected that the IPS will have to process approximately 200 kilograms of xenon propellant. Some performance numbers are summarized in Table 1. The columns highlighted in red represent the two operating points designated for this mission.

[illegible]			
Operating Point	1	2	3
Power into PPU (W)	750	700	650
Isp (s)	2736	2736	2736
Efficiency (%)	52	52	52
Thrust (mN)	28.9	26.9	25.0

Table 1 Ion thruster operating points

The IPS on board of the spacecraft is made up three primary subsystems. Each of these subsystems performs a specific task and will be described in greater detail in the following paragraphs. A graphical representation of the IPS is shown in Figure 1.

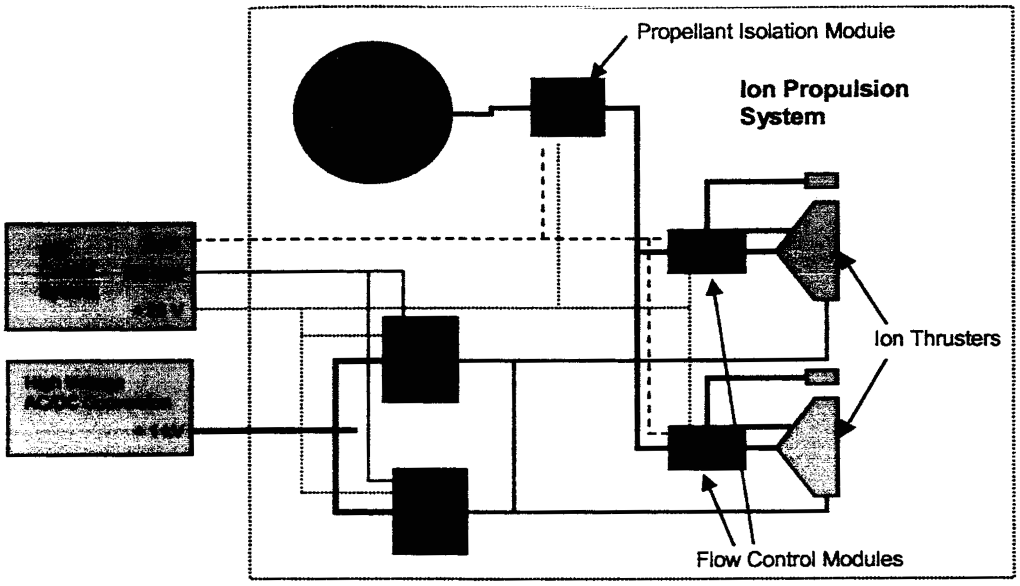

Figure1 Schematic of the Ion Propulsion System

The Power Processing Unit (PPU) receives power from the spacecraft power system (the RPS) and supplies the correct currents and voltages to the Ion thruster. It is assumed +28 Volts DC and 1000 Volts DC comes from the RPS. With high voltage power from RPS, the PPU size is reduced. A generic Ion thruster PPU is shown in Figure 2.

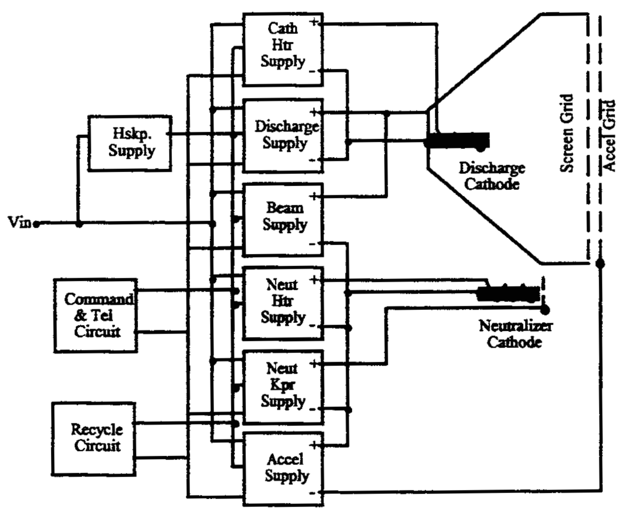

Figure 2 Schematic of a generic Power Processing Unit

There are two PPU's on board the spacecraft; one PPU is a back-up. Each PPU has the ability to control both thrusters. Finally, each of the PPU's will be capable of handling two distinct power levels (750 Watts electric and 650 Watts electric).

The PMS makes use of chemical etching technology. This technology is similar to the technology used MEMS, except that metal is etched instead of silicon. Individual PMS modules consist of multiple stacked layers of etched metal or plastic sheets. When these layers are stacked together, all of the internal flow passages are formed. This technology dramatically reduces size and weight of individual PMS components, which is extremely important for small spacecraft. The modules within the PMS are self-contained. Each individual module contains all required valves and sensors to carry out its designed- for task. The only external components are interconnecting tubing and cabling, still much reduced compared to standard PMS's.

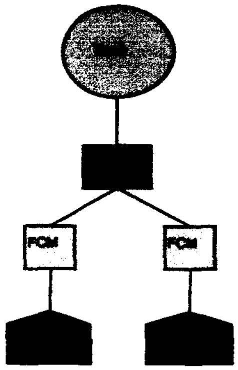

Figure 3 Schematic of the Propellant Management System

The spacecraft PMS is made of an isolation module and two flow control modules (FCM), as shown in figure 3. The isolation module separates the xenon tank from the flow control modules and ion thrusters. There is one isolation module per xenon tank. The FCM's provide the correct flow rates to the discharge cathode, neutralizer cathode, and main chamber. There is one FCM for every thruster onboard the spacecraft. Going to smaller and smaller Ion thrusters presents technical challenges.

The Ion thruster takes processed power from the PPU and creates thrust. A generic electron bombardment thruster is shown in figure 4. The major components are the discharge cathode, discharge chamber, screen grid, accelerator grid, neutralizer cathode, and the magnet rings.

A brief description of each of the major components is provided in Figure 4. Neutral propellant gas is admitted to the discharge chamber. The discharge cathode emits a mixture of electrons, ions, and unionized gas. The high energy electrons serve to ionize the neutral gas molecules in the discharge chamber and plasma is created. Ions close to the screen grid are extracted from the volume discharge, and the potential difference between the two grids accelerates them into space, creating thrust. The "neutralizer" cathode does not neutralize individual ions (through recombination) exiting the thruster, instead it serves to "neutralize" the cloud of positive ions behind the thruster. A cloud of positive ions would tend to fly apart, due to electrostatic forces, and not necessarily in the direction useful for producing thrust.

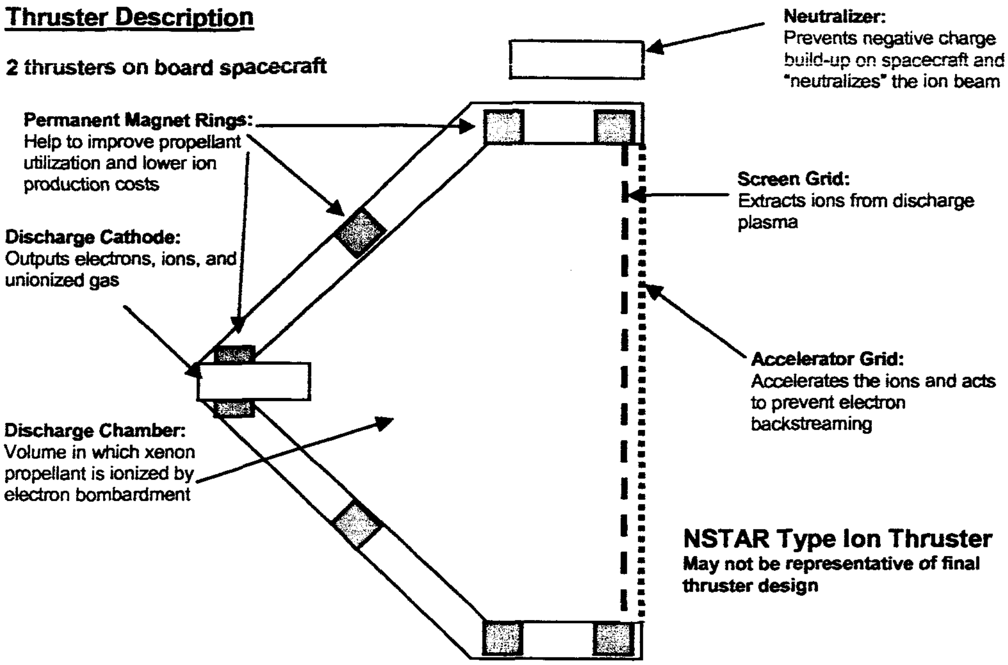

Figure 4 Typical NSTAR like Ion thruster

The remaining paragraphs describe technologies that are being looked at to increase the lifetimes of Ion thrusters, some of the difficulties that occur when scaling down Ion thrusters, and impacts that an IPS can have on the spacecraft.

Maintaining high discharge efficiencies become harder when scaling down to reduced powers and sizes. Scaling down the diameter of an Ion thruster (at constant length) tends to increase the probability that an ion will recombine at the wall (instead of being extracted into the ion beam). This leads to higher discharge losses. At lower thruster powers the discharge power is a much larger fraction of the total power. Minimizing the Ion Production Cost (defined as the ratio of input discharge power to ion beam current) becomes extremely important. Decreasing discharge chamber length increases neutral loss rate (lower propellant utilization). To help maximize overall efficiency of thruster, discharge losses should be minimized. Minimizing the ion production cost requires optimizing the chamber length, magnetic field shape, and the magnetic field strength (for a given diameter).

Several technologies are being researched to improve the lifetime of ion thrusters. The primary failure mechanisms in current Ion thrusters is erosion of the optics (screen grid and acceleration grid) from charge exchange ions, and discharge cathode failure from erosion or emitter material depletion. Technologies that attempt to solve discharge cathode erosion include electrodeless plasma production schemes such as microwave electron cyclotron resonance (ECR) and radio frequency (RF) excitation. Another school of thought chooses not to eliminate the hollow cathode, but to improve upon its design. Most research in improving lifetimes of the ion optics focuses on coming up with better materials or physical designs.

In microwave ECR thrusters, microwaves at a frequency equal to the electron cyclotron frequency are used to pump energy into the neutral gas. The electrons gain energy continuously, and eventually ionization occurs as electrons ram into neutral atoms. ECR plasma production is limited by the lifetime of the power tube (lifetimes of ~ 10 years have been demonstrated). High xenon gas purity is not needed, and ECR discharges operate as reduced plasma potentials which help to lower sputter erosion of the screen grid. In typical RF discharge thruster an induction coil is wrapped around the discharge chamber and excited by passing a current through it. The current induces an electric field which ionizes the neutral gas and creates plasma. RF thrusters still use a traditional neutralizer cathode, and thus lifetimes are still limited to approximately 30,000 hours.

Instead of getting rid of the hollow cathode, one can also attempt to improve its design. Most design improvements are of a materials nature. These include an erosion resistant cathode keeper, and advanced emitter material that has more barium and a lower work function.

Similar to improvements in hollow cathode designs, improvements in ion optics tend to be materials based. The general trend is a movement away from metallic grids, such as molybdenum, to materials that are less susceptible to sputtering. Two examples are carbon grids and pyrolytic graphite grids. Both reduce the sputter yield dramatically compared to molybdenum grids.

The IPS can have a number of effects on the spacecraft. These effects consist of interaction with the plasma, possible interference from fields, and contamination caused by sputtered atoms. The Ion thruster, along with the neutralizer, creates a plasma flow that can surround the spacecraft. This low energy plasma is made up of charge exchange ions and electrons from neutralizer. Charge exchange ions occur when an ion exchanges an electron with a neutral. The result is a high speed neutral and a low speed ion. The plasma can change the spacecraft potential, charge exchange ions may present risk to sensitive particle detection instruments, and spacecraft surfaces may sputter if exposed to direct impingement by energetic ions.

Contamination caused by sputtered molybdenum (if using molybdenum optics) can also occur. Sputtered neutral molybdenum atoms from the accelerator grid are ejected in the general direction of the plume. Charge exchange can then take place, and molybdenum ions can follow electric field lines and move "upstream" of the thruster.

Lastly, interference from the many fields the thruster produces may arise. Electromagnetic fields arise from current fluctuations in the ion propulsion system. This may have possible impacts on communications system and fields measurements made by certain instruments. Permanent magnets in the ion thruster cause DC magnetic fields, which can affect magnetometer readings.