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Report Title:

Low cost space transportation using a stable plasma for energy storage

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PREFACE

This report was prepared for NASA Institute for Advanced Concepts NIAC CP 98-01. The contractor is Electron Power Systems (EPS), Inc.

The stable plasma was first discovered in 1985. It was initially called the Electron Spiral Toroid (EST). The initial theory and testing were privately funded, with the first patent issued in 1992. NASA provided initial research funding in 1995. In 1996 the Army Research Laboratory had ten scientists review the theory and agreed the EST is a potential energy storage breakthrough. Based on this recommendation, the Army Research Office funded a project for MIT to study the stability and energy loss of the EST in 1996. The present BMDO STTR contract (with DTRA acting as the technical representative) continued the study of the stability and energy loss of the EST and demonstrated the experimental scaling of small EST's.

Special acknowledgment is given to Dr. Chen and Dr. Temkin of the MIT Plasma Science and Fusion Center who have raised many initial questions about the EST technology, and have worked with Electron Power Systems to find answers. Dr. Chen has worked over the past five years part time to independently derive and confirm the physics of the EST, and detail the results in a report of 80+ pages. Dr. Temkin has reviewed Dr. Chen's work, and has also made many suggestions that have guided the experiments by the author.

Thanks also to Dr. W. J. Guss who has reviewed this report and made many constructive suggestions. His help in designing the experiments has been invaluable. Thanks also to D.C. Seward, son of the author, who has helped develop the technology over the past ten years.

SECTION 1: INTRODUCTION TO THE STABLE PLASMA TECHNOLOGY

1.1 EXECUTIVE SUMMARY: REASON FOR THE PROJECT:

A revolutionary technology for propulsion and energy storage has been discovered which could potentially reduce the cost of a Mars mission by more than 90%. This Phase I project demonstrated the feasibility of attaining specific impulses of 60,000 seconds, which could potentially reduce space travel fuel requirements by 95%. In addition, this Phase I project demonstrated the feasibility of space energy storage systems which would potentially have 95% less mass than radioisotope supplies, while storing similar amounts of energy. The results were compared to a suggested Mars mission plan, and a saving in cost of more than 90% was calculated.

This revolutionary technology is based on the newly patented stable plasma technology. Stable plasmas need no external magnetic fields for containment, and potentially store large amounts of energy as internal magnetic field energy with virtually no mass. Propellant is energized for thrust without combustion, potentially producing specific impulses of 60,000 seconds vs. 500 seconds for chemical propulsion. Stable plasma specific energy is potentially $6.3E16$ joules/kg, compared to liquid Hydrogen with $1.2E8$ joules/kg.

The stable plasma technology is being developed rapidly. A research scientist at the MIT Plasma Science and Fusion Center has independently derived and confirmed the physics that stable plasmas exist and need no external magnetic fields. Consistent with that theory, stable plasmas are being created in the lab of EPS, Inc. Funding sources include NASA, US Army, BMDO, and USAFOSR, and private investors.

The stable plasma technology will enable key parts of the NASA three pillars for success, significantly reducing the cost of space transportation as follows:

- * A concept jet engine is described that heats air without combustion, needing no fuel, thus reducing jet plane costs by more than 50%, and emissions by more than 90%.

- * A concept design of a stable plasma space propulsion system is described that will increase specific impulse of propellants to more than 60,000 seconds, compared to 500 for chemical rockets, allowing for a proportionate reduction in fuel mass and cost.

- * A concept energy storage and power conversion system is described that has less than 5% the mass of a comparable radioisotope supply.

- * A launch concept is described using the jet engine as the first stage, which will reduce launch costs for a Mars mission by more than 90%.

The Phase I project demonstrated the feasibility of low cost space transportation based on stable plasma technology. The Phase II project will extend this concept design to detail the costs and developments required to turn this emerging technology into useful space transportation systems.

1.2 INDEPENDENT CONFIRMATION OF THE STABLE PLASMA TECHNOLOGY.

When a revolutionary concept is put forward, care must be taken to ensure the concept conforms to known laws of physics. Over the past ten years the theory of the stable plasma has been set down by the author, then given to some of the best plasma scientists for independent confirmation.

Dr. Chen, a Research Scientist from the MIT Plasma Science and Fusion Center, has independently reviewed the stable plasma technology over the past five years. He has independently derived the physics [Chen 1999]. In a report to the BMDO (Ballistic Missile Defense Organization) as part of an STTR contract, Dr. Chen confirmed that a generic class of stable plasmas has been found which is stable with no external magnetic field required for containment. This is an especially important result since it agreed with the experimental evidence observed by Seward at Electron Power Systems, Inc. This is potentially a major discovery, since a stable plasma occurring in atmosphere, with no applied external magnetic field, has not been described in the technical literature to date.

In a previous report to the ARO, Dr. Chen stated that the technology " ... faces no fundamental physics limitations." The ARO let an STIR contract to EPS, Inc. in September 1996 to help fund the work by Dr. Chen of MIT. Other conclusions by Dr. Chen:

1. The equilibrium shape is a hollow plasma with a thin outer shell of electrons.
2. His analysis "...supports the experimental observations of the [stable plasma] by Seward..."
3. The electron temperature is extremely low, "... which may suggest the electrons are strongly coupled, as shown by Seward."
4. "... the [stable plasma] equilibria exist in the absence of any applied toroidal magnetic field."
5. "No upper limit has been found on the energy density in the [stable plasma]."

In 1996, ten scientists from the ARL read and reviewed the stable plasma theory. They reported that the stable plasma is "a potential energy storage breakthrough."

The above review process has led to an independent review and derivation of the physics of the stable plasma. There is no peer-reviewed literature at this time since the development has been proprietary and funded with private investment and with research contracts. There are three published patents, one international application published, and three other patents applied for. [Seward 1992, 1996a, 1996b, 1998a].

Please note that the independent confirmation to date by MIT relates to the stable plasma itself, and has been completed as of March 1999. Confirmation of the applications is in process, and for this report, Dr. W. J. Guss has reviewed them.

1.3 STABLE PLASMA DESCRIPTION AND INITIATION.

The stable plasma stores energy as magnetic field energy as shown in Fig. 1. It is a hollow toroid of electrons, with all electrons spiraling in an ordered structure in a thin outer shell. Since all electrons are in parallel paths, they create a large electrical current, which in turn creates a large internal magnetic field for storing energy. The stable plasma provides magnetic field energy storage in a vacuum containment without needing external magnetic fields other than for initiation. The technology is detailed in references [Chen 1999], [Seward 1998c] and summarized here.

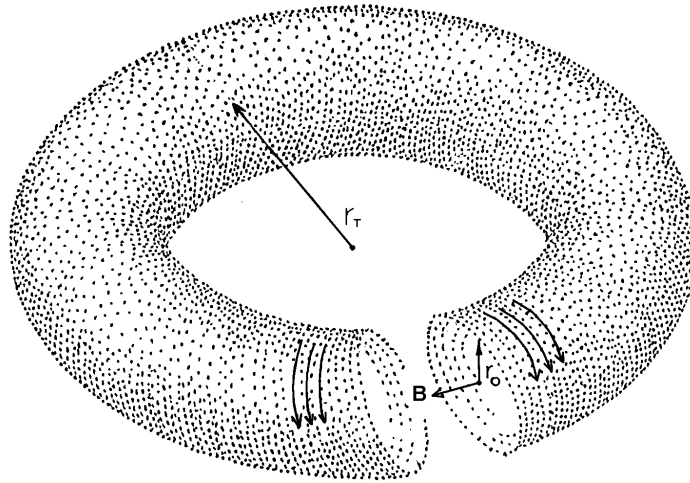


Figure 1. Stable plasma schematic showing direction of electron flow, hollow construction, and internal magnetic field.

To initiate a stable plasma, an electron beam is trapped in a circular magnetic field as shown, causing the electron beam to spiral.

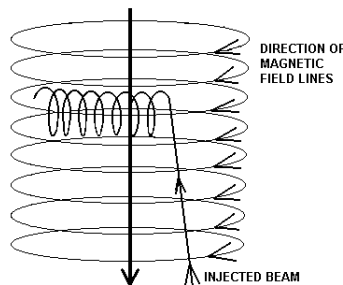


Figure 2. Electron beam trapped in a circular magnetic field.

Since the magnetic field is circular, the electrons will spiral around the magnetic field and rejoin itself, with proper initial conditions, a unique feature of the stable plasma. It is shown schematically in Figure 3, and further described in the references. During the spiraling, ions are trapped internal to the spiral path, ensuring charge neutrality overall.

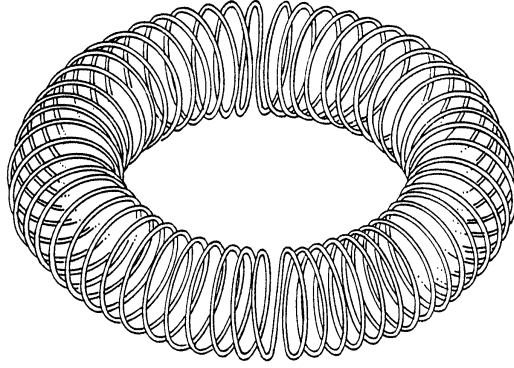


Figure 3. Stable plasma schematic.

Once a stable plasma is established, the electrons will spread out into the thin sheet as shown in Fig. 1. The electrons are in parallel orbits and at the same velocity since they all come from the same electron beam. When the energy between adjacent electrons is close enough and if the density is high enough, the electrons will couple together to form an electron shell. For strong coupling of electrons to occur, the coupling constant Γ must be greater than one. From [Gilbert 1988], the coupling factor is:

$$\Gamma = (1/k_B T)(q^2/4\pi\epsilon_0)[4\pi n_b/3]^{1/3} \quad (1.0)$$

where T is the difference in energy between electrons, and n_b is the electron density. It is important to note that T relates to the difference in energy, and not to the absolute energy. Γ for the stable plasma electron sheet has been independently confirmed as in excess of 170.

Once the stable plasma is formed it will remain stable as long as the coupling factor conditions remain satisfied. The external initiating magnetic field can be removed. The system is charge neutral due to the ions remain trapped internal to the stable plasma.

The central magnetic field is $B = \mu_0 N I$ where N is the number of parallel paths or orbits, and I is the orbit current. $I = qV/D$ where q is electron charge; V is velocity; and D is electron spacing. Total energy is $U = B^2 / 2\mu_0$.

The stable plasma can be thought of as having a structure. A balance of forces determines its shape [Seward 1996].

Once the stable plasma is formed and captured in a containment, energy can be added. Energy is added separately using microwave energy. This is described more fully in Section 3 describing power supplies.

1.4 EXPERIMENTAL EVIDENCE

EPS, Inc. has conducted proof of concept experiments over the past ten years on a proprietary basis. The results have confirmed much of the theory. Experiments have resulted in the creation of many stable plasmas.

Most of the work to produce and measure the stable plasmas is proprietary at this time. The USAFOSR, BMDO, and the US Army have reviewed it on a non-disclosure basis, have found it a potential breakthrough, and have funded it. MIT has independently reviewed and derived the physics, and has confirmed the existence of stable plasmas. MIT has also agreed the experimental results are consistent with the theory. More results will be published in 1999 and 2000.

The experimental apparatus is an extension of the apparatus detailed in the patents, with enhancements. The electron arc supply is capable of producing an electron arc in atmosphere. It is an assembly of batteries capable of producing 1500 amperes at up to 500 VDC. The arc is initiated in a bell jar where the atmosphere can be controlled.

Using the proprietary apparatus, an electron beam of 750 amperes was generated at 150 VDC. The event was recorded on various instrumentation, including video cameras. An experiment lasts for less than 3 seconds. Several hundred experiments have been run and recorded where many stable plasmas have been observed and recorded. Their size is measured to be 1mm to 1 cm in total toroid diameter, and 1 mm to 3mm in orbit diameter. Duration: more than 600 milliseconds observed.

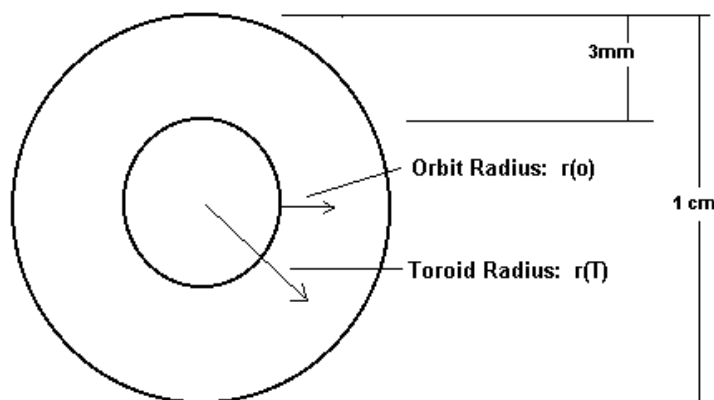


Figure 4. Drawing of observed stable plasma.

Work is being funded to increase the size of the stable plasmas. The stable plasmas observed to date are small and hold only a fraction of the potential total energy. For them to contain a large amount of energy, energy must be added. Several methods of adding energy have been proposed. Microwave is the most likely candidate as it is presently used to add energy to plasmas. A stable plasma of the size observed (0.005 m radius, 0.0017 orbit radius) could hold up to 18 kilojoules if energy is added.

1.5 STABLE PLASMA PROPERTIES:

Total Energy: Large amounts of energy can be stored in the stable plasma.

TABLE 1-1 Stable plasma energy storage parameters.

Total Energy (J)	Major Radius (m)	Minor Radius (m)	Area (m ²)	Containment (Kg)
10 ⁸	.30	.1	1.2	6
10 ⁹	.48	.16	3.0	15
10 ¹⁰	.76	.25	7.5	38
10 ¹¹	1.2	.40	18.7	94
10 ¹²	1.9	.63	47	235
10 ¹³	3.0	1.0	119	595

Note: The mass shown is energy and containment only, and does not include conversion of the energy into electricity.

Containment: this requires a vacuum containment with a metal protective cover. Calculated values for mass are shown in Table 1-1, based on 5 kg per square meter.

Size: Stable plasma size vary greatly depending on the initiating conditions. The values shown in the table are representative, and may vary for a specific application.

Energy Addition and Removal: Microwaves add energy to the stable plasma at an absorption efficiency of approximately 70%. Once the stable plasma is established, energy can be added to increase magnetic field energy as required (Seward 1996). Energy can be removed in a variety of ways: heating of a propellant gas; microwave energy, or electron packets.

Safety: The stable plasma is non-nuclear, and non-polluting. It is stable, which means it will hold itself together without any external magnetic fields. Analysis indicates the stable plasma will recover from perturbations and will remain stable. There is no known or obvious normal occurrence that will lead to instability. Stability testing will be part of all testing programs in the future.

Operating Temperature: From a few degrees Kelvin, to many thousands of degrees.

Specific Energy: An electron volt (eV) is 1.602E-19 joule (J), and an electron mass is 9.11E-31 kg, resulting in 1.76E11 J/kg per eV. Since each electron has an ion associated with it to ensure charge neutrality, the specific energy for an electron/ ion pair is 9.6E9 J/kg at 100 eV.

The specific energy of a stable plasma is actually greater than just the specific energy of the electron/ion pair since most of the energy is contained in the internal magnetic field that has no mass. The magnetic field will contain more than 99% of the energy and has no mass. For example, a stable plasma with 1.0E10 joule would have

specific energy of $6.3\text{E}16$ J/kg, exclusive of containment. The following compares specific energies:

Lead Acid Batteries ¹	$1.1\text{E}5$ J/kg
DOE Battery Goal ¹	$7.8\text{E}5$ J/kg
Gasoline ¹	$4.2\text{E}7$ J/kg
Liquid Hydrogen	$1.2\text{E}8$ J/kg
Experimental 100 eV plasmas achieved at EPS, Inc.	$1.1\text{E}10$ J/kg
10,000 eV EST (calculated)	$6.3\text{E}16$ J/kg

Notes: 1. Economist, 10 October 1998, p86.

The above comparison shows a stable plasma will have far greater specific energy than gasoline or liquid Hydrogen. However, this does not compare complete systems. The containment is estimated in Table 1-1 above.

SECTION 2

STABLE PLASMA CONCEPT DESIGN FOR SPACE SYSTEMS

2.1 GENERAL

The concept design of a stable plasma is based on an extension of the proof of concept testing done to date [Seward 1998b], and the independent confirmation to date [Chen 1999]. The plasma is designed to have $10E10$ joules of energy stored as magnetic field energy in the intense magnetic field internal to the plasma. This section will provide the calculations for the stable plasma design, and will discuss the uncertainties that remain to be addressed.

2.2 STABLE PLASMA

The stable plasma is initiated using the proprietary technology of EPS, Inc. [Seward 1992, 1996a, 1996b, 1998a]. The following example stable plasma has been constructed using a computer model developed from the theory.

Parameters of the example stable plasma:

Diameter, major, r_T :	0. 63m
Diameter, minor, r_O :	0. 21m
Electron energy:	10,000eV
Electron velocity:	2.96E7 m/s
Pressure of containment:	1.0E-10 atmosphere for storage
Coupling factor:	743 (Note: must be more than 170).
Total Charge:	186 coulombs (Note: system is charge neutral)
Mass (stable plasma only):	1.86E-6 kg
Number of orbits:	3.4E10
Orbit Current:	0. 38 amperes.
Magnetic Field:	16,587 Tesla
Energy Loss, Radiation:	1.16J/sec (note: synchrotron radiation)
Energy Loss, Collisions:	8.9E-10 J/sec
Total Energy:	1.91E12 J
Energy Extraction:	1790 J/sec at pressure @ 100 atmospheres.

2.3 DISCUSSION

Stable plasmas have been created in proof of concept experiments. Work is in progress to expand the proof of concept results into a full demonstration model. The full demonstration model will be 2.5 cm diameter, and positioned such that measurements can be made reliably. The energy loss rate will be definitively measured. Energy will be added in a measurable manner. This following is a discussion of the main hurdles that need to be overcome in order to produce a demonstration unit.

1. Initiation status: This is the top priority area of experiments at this time. A new stable plasma generator has been designed and built at EPS with private funding, to include new test instrumentation. It was completed in December 1998, and experiments are ongoing. The first set of experiments will result in specific measurements of the stable plasmas. BMDO and private investors are funding this work. Specific tasks include:

1.1. Determine the effects of pressure and current on stable plasma formation by developing curves of current vs. pressure vs. size.

1.2. Measure the stable plasma trajectory, and whether it will be altered with an E field or with a B field.

1.3. Verify theoretically the loss mechanisms of the stable plasma and relate them to the values measured in the Phase I project.

2. Size: The largest stable plasmas observed to date have been under one cm. Using the measurements of the properties listed above, a stable plasma of 2.5 cm diameter will be made.

3. Energy Addition: It is well known that energy can be added to a plasma using microwave energy [Seward 1996b]. It is assumed for this concept design that this approach will apply here. This remains to be demonstrated. BMDO and private investors are funding work to accomplish the following:

3.1 Design an experiment to add energy to the stable plasma.

3.2 Add energy to an stable plasma and remove it in a measurable experiment.

4. Positioning: The method of holding a stable plasma in place has been proposed previously [Seward 1996b]. A wire through the center of the toroid will have a small positive charge, and as such will hold the plasma in place. Similarly, plates above and below the plasma will have positive charges, and will serve to center it. Note that the EST has an overall slightly positive charge, since it has both electrons and ions in nearly equal numbers to minimize space charge. The number of ions is approximately 2% greater than the number of electrons.

5. Collisions: The best method to remove energy from the stable plasma appears to be through collisions with background gas. Gas is injected into the plasma chamber where it collides with the plasma surface and is heated in turn. The amount of energy extracted is a direct function of the amount of pressure in the chamber. The rate of energy loss due to

background collisions has been estimated based on proof-of-concept data [Seward 1998b]. This is a preliminary result, and needs better experimental data. Synchrotron radiation is also a loss mechanism. However, it is calculated to be small at 10,000 eV.

6. Containment: The containment in its simplest form is a vacuum chamber. A vacuum bell jar is used in proof-of-concept experiments. The containment would vary with the specific application. The rate of energy extraction is a function of pressure, so for larger power supplies a higher pressure might be needed as well as a more robust pressure chamber. For propulsion, the containment would be the equivalent of the combustion chamber in a typical rocket engine or jet engine, which would seem to avoid adding any mass penalty [Seward 1996b, 1998c].

7. Prototype: Once a 2.5 cm stable plasma is established, it will be a relatively straight forward matter to increase the current and create a stable plasma of 60 cm diameter. This would be the prototype energy storage device for an electric vehicle. This prototype would also demonstrate the use of the stable plasma for propulsion.

2.4 COST

1. Cost of the initiation apparatus: The stable plasma initiation is done on an experimental apparatus that can be reproduced for approximately \$500,000. The initiation apparatus required for a space system stable plasma will cost between \$1M and \$5M. A detailed estimate is not presented here, but is available on a non-disclosure basis.

2. Cost of the stable plasma: Once the initiation apparatus is in place, the cost to produce a stable plasma is small, and is estimated at \$100 to \$1000, not including the stored energy. The present cost of one initiating experiment is \$1000 and produces many stable plasmas. There is every reason to expect that a large stable plasma can be produced in a single initiating event, and will cost about \$1000.

The cost of the containment is the cost of the vacuum chamber in which it is held. It will vary from mission to mission, and will start in the range of \$1000. If the stable plasma is used for power generation, a pressure container will be required, which could cost up to \$20,000.

3. Cost of the stored energy: The stable plasma needs to be filled with energy. The stable plasma proposed has 1.0×10^{12} Joules, which equates to 2.7×10^5 kilowatt-hours. A kWh of energy costs \$0.07 on a commercial basis, and is estimated at \$0.02 to produce locally.

There is an efficiency loss in transferring the energy from electric power into the plasma that needs to be considered. The plasma will absorb 70% to 80% of applied microwave energy, based on the method used to heat plasmas today. Additionally, the conversion from electric power to microwave is estimated at 70% efficiency. The combined efficiency is therefore estimated to be 50%.

The cost of a 2.7×10^5 kWh load of energy will be approximately \$18,900.

SECTION 3

SPACE SYSTEM POWER SUPPLY DESIGN

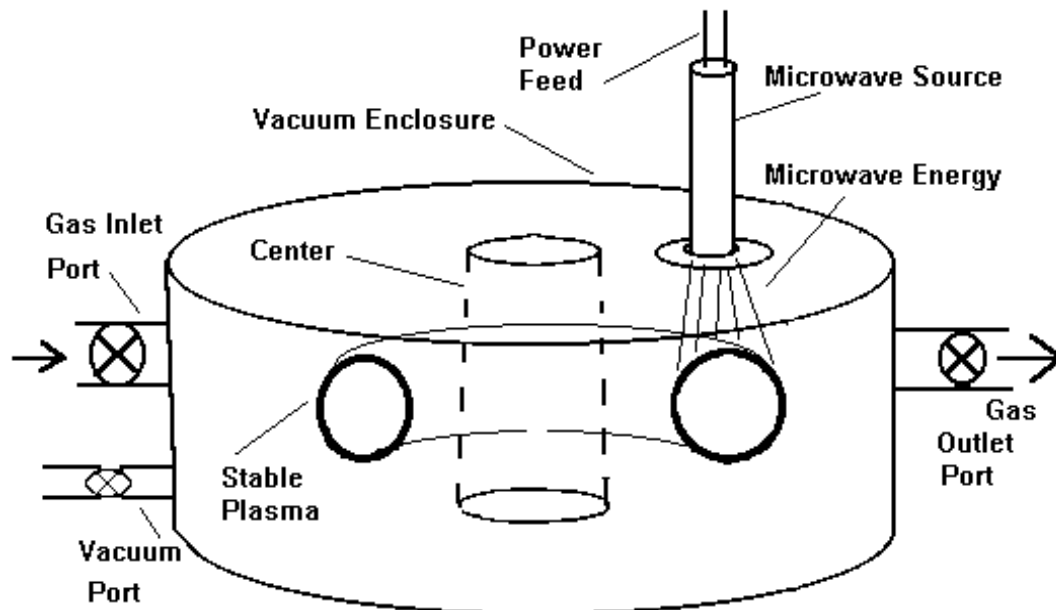
3.1 GENERAL

A space system power supply based on the stable plasma would provide NASA a potential mass saving of 95% vs. the radioisotope supply. The design of a stable plasma power supply in this section is based on the stable plasma from the previous section. The plasma is designed to have 1.0×10^{12} joules of energy stored as magnetic field energy in the intense magnetic field internal to the plasma.

The energy in the intense magnetic field of the stable plasma can be extracted by causing collisions between the background gas and the stable plasma surface. The pressure in the plasma enclosure can be increased or decreased, and in that way the energy can be extracted at a greater or lesser rate. The energy is extracted as heated gas that can be used in a number of ways to generate electricity. For illustration, this design will use thermal electric cells to produce electric power, the same method selected by NASA for the deep space probe. This will allow a comparison to the radioisotope supply.

3.2 CONTAINMENT OF THE STABLE PLASMA

The stable plasma is contained in a vacuum enclosure in order to control the rate of extraction of the energy. This is shown schematically in Figure 3.1 below. Energy can be added to a plasma using microwave energy as shown.



.Figure 3-1. Stable plasma in containment.

The center post in the vacuum enclosure will have a small positive charge, and as such will hold the plasma in place. Similarly, the surfaces above and below the plasma will have positive charges to center the plasma. Note that the plasma itself has an overall slightly positive charge.

3.3 ENERGY EXTRACTION

Gas can be added to the enclosure. It will be heated through collisions with the stable plasma surface. The heated gas will heat the vacuum enclosure. The rate of energy extraction is directly proportional to the pressure of the gas in the vacuum enclosure.

A thermal-electric cell from Advanced Modular Power Systems, Inc. (AMPS) produces the electricity for this power supply. NASA has selected this cell for a deep space power system. A single thermal-electric cell produces 7.5 watts at 25% efficiency in a 125-gram package. A thousand-watt power supply would require 134 of these cells, which would have total mass of 16.75 kg. This is an expensive approach since the thermal cell is still in a prototype stage, but costs are expected to improve with time.

3.4 COMPARISON OF POWER SUPPLIES

Battery power supply vs. the Stable Plasma power supply:

	Stable Plasma Supply	Battery Supply [Keener 1998]
Total Energy	2.5E5 kW-hr	2.5E5 kW-hr
Power	1000 watts	1000 watts
Storage mass	5 kg	2500 kg
Power converter mass	16.75 kg	N/A
Specific energy	1290 watt-hr/kg	100 watt-hr/kg
Environmental hazard	None	Toxic chemicals

The plasma supply will store the energy with little mass. There is a substantial mass associated with the power converter that is based on the thermal cells of AMPS, inc. The present cost of the thermal cells is high since they are still in the prototype stage, but are projected to come down over time. The battery supply loses significant energy over time, which need to be factored into any specific mission requirement. The stable plasma power supply would have 22 kg total, or 0.9% of the mass of a battery supply, a mass savings of more than 99%.

Nuclear power supply vs. the Stable Plasma power supply:

	Stable Plasma Supply	Nuclear Supply [Difilippo 1998]
Total Energy	10E16 joule	10E10 joule
Containment/shield	1 kg	10,501 kg
Pressure vessel	519 kg	519 kg
Power supply/1kwatt	<u>17 kg</u>	<u>17 kg</u>
Total	537 kg	11,137 kg

This comparison shows that the main advantage of a stable plasma over a nuclear reactor is the elimination of the shielding, for a substantial savings in mass. The power generated will be the same in both cases, so the same pressure vessel mass was used, as well as the same power supply. The stable plasma power supply would have 4.8% the mass of the radioisotope supply, a mass savings of 95%.

The uncertainty is the rate of energy extraction from the stable plasma. Proof-of-concept measurements have indicated the energy extraction rate will be useful and controllable. However, until this has been confirmed on a larger scale, it remains uncertain.

SECTION 4.0

PROPULSION IN AIR USING A STABLE PLASMA

4.1 GENERAL

The NASA three pillars for success has goals of reducing air travel cost by 25% within ten years, and reducing aircraft emissions by 67% within ten years. A jet engine built around the stable plasma can meet both these goals as shown by this concept design.

A stable plasma will potentially replace jet fuel with energy stored as magnetic field energy. Magnetic field energy has virtually no mass. For comparison, in an F-22, 30,000 pounds (13,636 kg) of jet fuel (6.5E10 joules of energy) could be replaced with a stable plasma and its containment of 207 pounds (94 kg).

A stable plasma powered F22 would need modified jet engines and no fuel. There would be no combustion. Air is compressed as in a conventional jet engine, then brought in contact with the stable plasma where it is heated. Heated air then expands to produce thrust. The takeoff weight of a stable plasma powered F22 would be approximately 30% of an F22.

4.2 CONCEPT DESIGN OF A STABLE PLASMA JET ENGINE

Referring to Figure 4-1, air (1) will be drawn into the compressor stage (2) as in a conventional jet engine. The compressed air will be brought into contact with the stable plasma in the heating chamber (3). The air will be heated without combustion, and expanded out the exit nozzle (4). The exiting air (5) will create thrust.

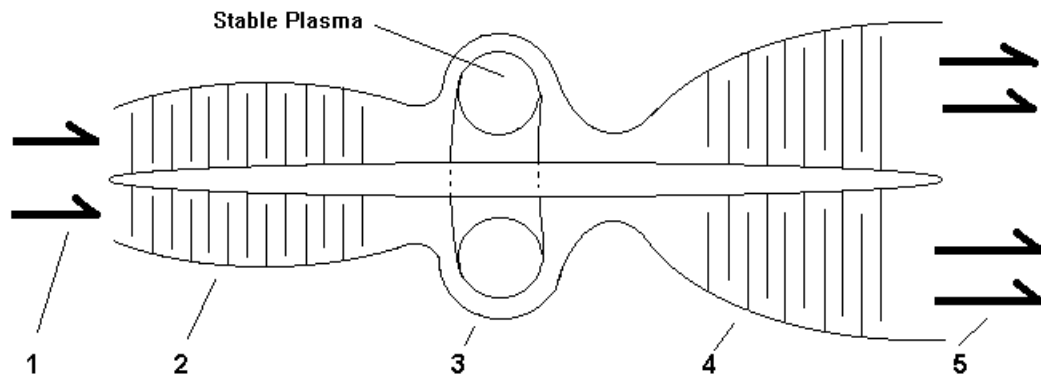


Figure 1. The Stable Plasma Jet Engine.

In the stable plasma jet engine, fuel mass is replaced with magnetic field energy with virtually no mass, which will greatly reduce the size and mass of aircraft. The process is environmentally benign, since it does not use jet fuel, and emissions from combustion would be reduced to zero.

From Table 1-1, it is feasible that a greater amount of energy can be stored in the stable plasma so that an aircraft can be fueled in the US and fly around the world without refueling. This would give a great advantage over conventional jet aircraft used by the military that require in-air refueling from remote bases. Table 1 includes representative values only. There are an infinite number of variations in size and energy, and the stable plasma can be sized for a particular mission.

Energy can be added using microwaves to increase magnetic field energy as required. Energy can be removed by heating air. The stable plasma is non-nuclear, non-polluting, and safe to use near people. An established stable plasma will store electrons for a long period of time. Since no external magnetic field is required for containment, losses will be low.

4.3 COMPARISON OF THE PLASMA JET ENGINE TO A COMBUSTION JET ENGINE

SPECIFIC IMPULSE: The air in the stable plasma jet will be heated to the same temperature as the air plus fuel in a conventional jet. The exhaust velocity will be substantially the same for both types of jet engine. The specific impulse of the air will therefore be the same in both cases.

EFFICIENCY: The heat absorption process is usually quite efficient, in the range of 90%. However, in this case, the air will be moving at a high velocity, which will alter this number. Until the process of collision with the surface is better understood, it is not clear what the efficiency will be. It could range from 90% to 70%, which is the range of present jet engines. This question will be addressed further in planned experiments.

AIRCRAFT COST: The stable plasma jet will require no fuel, nor the tanks or lines associated with fuel. The result will be a reduction in takeoff mass of an aircraft by approximately 70%. This reduction in mass would allow for a reduction in engine size also. It is not easy to estimate the resulting cost reduction, but it would be in the range of 50% to 70% of the total airframe and engine costs.

EMISSIONS: There will be no combustion emissions.

NASA THREE PILLARS FOR SUCCESS: Ten individual objectives are defined. This jet engine will address three as follows:

- Reduce emissions by a factor of three within ten years. This design will do that.

- Reduce noise levels by a factor of two within ten years. This design will do that since the size of aircraft will be reduced by 50% to 70%.

- Reduce cost of air travel by 25% within ten years. This design will do that.

SECTION 5.0

SPACE PROPULSION CONCEPT DESIGN

5.1 GENERAL

The stable plasma can be used for propulsion in space [Seward 1998c]. Stable plasma propulsion will potentially achieve specific impulses more than 60,000 seconds. To be useful, the magnetic field energy of the stable plasma needs to be converted to propulsion energy. Two ways for this to be done are considered here. First, a gas can be introduced into the plasma chamber where it will collide with the plasma, gain heat energy, and then can be ejected for thrust. This is a simpler approach, but will be limited to a specific energy similar to rockets. Secondly, small stable plasmas can be created, using the stable plasma power supply, then accelerated for thrust in a manner similar to a scaled up pulsed plasma thruster system. This is a feasible approach, and will produce high specific impulses.

5.2 SPACE PROPULSION UTILIZING GAS PROPELLANT

Propulsion can be created without combustion using the air breathing jet engine from the previous section. The advantage of heated gas propulsion over a chemical rocket is that it can launch from earth and get through the earth's atmosphere without using any propellant. This could result in the elimination of the first stage of a three stage rocket, and would eliminate approximately one half of the take-off mass.

Once above the atmosphere the system would have to operate differently. When there is no longer enough air to create suitable thrust, the intake of the jet engine could be closed, and a propellant gas would be injected directly into the intake where it would be heated by the stable plasma and ejected for thrust. This method of propulsion is described here first since it is the easiest to compare to chemical rockets.

Once above the atmosphere, for launch into orbit or for space travel, all gas propellant would need to be carried on board. The specific impulse of gas propellant used for propulsion in this manner would be similar to that of rocket fuel. This is limited by the heating of the mechanical components such as the nozzle and combustion section, the same as in present rockets. The gas can be heated to the same exit temperature as in a rocket using well-known design techniques. Gas heating by the stable plasma has been demonstrated in the proof-of-concept testing.

The gas propellant can be any gas. This is an advantage, since a low cost gas such as air or nitrogen can be used. Also, in space, it would be possible to obtain more gas propellant from any gas source. For example, on a Mars mission, propellant to get there would need to be carried, but propellant for the return trip could be obtained from the atmosphere of Mars, eliminating the need to launch the return propellant mass.

As an example, a comparison can be made to a Pegasus rocket [Jane's 1998], a small three-stage launch vehicle that has wings. The Pegasus is launched from an aircraft. It then uses rocket fuel to propel it through the upper atmosphere and into orbit.

	Pegasus	Concept stable plasma launcher
Stage 1 mass:	1,868 kg	934 kg
Fuel:	12,152 kg	6050 kg

Note: half the fuel of Pegasus stage 1 is expended to get out of the atmosphere [Jane's 1998], and the stable plasma jet engine would not require this fuel.

Stage 2 mass:	346 kg	346 kg
Fuel:	3,024 kg	3,024 kg
Stage 3 mass:	122 kg	122 kg
Fuel:	<u>771 kg</u>	<u>771 kg</u>
Payload (polar):	<u>200 kg</u>	<u>200 kg</u>
Total:	18,718 kg	11,447 kg (61%)

The cost saving is assumed to be the same as the mass savings, or 39%. Comparing this to a three-stage launch vehicle such as the Titan would provide an even greater saving since the Titan requires a larger first stage to get above the atmosphere. In the case of the Titan, the estimated cost saving is 50%.

5.3 STABLE PLASMA THRUSTER IN SPACE

Stable plasma propulsion could potentially achieve specific impulses more than 60,000 seconds. A project is in progress with the US Air Force to produce a feasibility study of this propulsion method, and it looks promising. A summary of the results to date is included here, and the final report will be available later this year.

Small stable plasmas can be readily produced using the proprietary technology from EPS, Inc. The small plasmas could in turn be accelerated by the pressure gradient in an applied magnetic field. Dr. Chen of MIT has suggested this method independently, based on the compact toroid work sponsored by the Air Force [Degnan 1993], [Kiutti 1994]. In that referenced work, compact plasma toroids were accelerated to a velocity of 1670 times the speed of sound using an applied magnetic field. The compact toroids in that referenced work were larger toroids than the stable plasmas. It seems reasonable that small stable plasmas can be accelerated to 6 E5 m/s.

The small stable plasmas in proof-of-concept experiments are predicted to contain 1.4E15 electrons and an approximately equal number of ions (mostly nitrogen ions). The total

mass of the stable plasmas is about $6.6\text{E-}10$ kg. They are produced at 19VDC, and the minimum energy to produce one would be 0.00426 joules. The actual energy needed to produce one in proof-of-concept experiments is approximately 60 joules. With development it is expected the energy to produce a small plasma will be 0.1 joule.

The energy to accelerate the small stable plasma is calculated to be 119 joules ($E = \frac{1}{2} mv^2$) to produce a 40 micronewton pulse. The acceleration is accomplished using magnetic coils. The thrust this will produce is 40 micronewtons per small stable plasma.

Increasing the number of stable plasmas accelerated can increase the total system thrust. The stable plasmas can be produced each 0.001 second in the present generator. There is no theoretical reason they can not be produced faster. A project has been authorized by the BMDO to study this further.

Increasing the size of the stable plasmas accelerated can increase the total system thrust. There is no theoretical reason stable plasmas can not be produced that are several orders of magnitude larger than the small stable plasmas above. The BMDO project will study this further.

The work to analyze the small stable plasma thruster is being funded by the Air Force and the BMDO. The work is not classified, and so is available for NASA use. The work is proprietary.

SECTION 6

LOW COST SPACE TRANSPORTATION

6.1 OVERVIEW

The use of a stable plasma for energy storage and for propulsion has the potential of producing a Mars ship that requires low cost space travel by reducing cost and mass for space propulsion, for power generation in space, and for launch from earth. Total propellant mass saving will be more than 90% and the cost savings would likely track that.

The saving will come from propellant and power supply mass. First, the specific impulse of a space propulsion system can be increased to more than 60,000 seconds, compared to 3000 for nuclear propulsion. Secondly, energy storage and power supplies will have 95% less mass than space radioisotope supplies. Thirdly, the launch propellant mass can potentially be reduced as much as 50% by using the stable plasma jet engine as a first stage launch vehicle.

6.2 COST SAVINGS FOR ENERGY STORAGE AND POWER SUPPLIES

Space power supply: The stable plasma supply will have 4.8% the mass of a radioisotope supply. For the example presented, a stable plasma supply will save 10,600 kg vs. the radioisotope supply. Launch cost will be 4.8% of the radioisotope supply. The power conversion will be the same for both supplies.

6.3 COST SAVINGS FOR LAUNCH

The stable plasma jet engine could be used to raise the launch vehicle through the atmosphere with no fuel as described in Section 4.0. The first stage of a Titan rocket is approximately used to lift the Titan and its payload through the atmosphere. Section 5.0 presents a concept design of a system to reduce launch fuel mass by about 50%. The stable plasma jet engine would also be reusable, resulting in vehicle cost savings.

6.4 COST SAVINGS FOR SPACECRAFT PROPULSION

Section 5.3 describes a new form of propulsion using stable plasmas. Small stable plasmas are made using generators similar to those used by EPS, Inc. The stable plasmas are accelerated with magnetic fields, producing a specific impulse of more than 60,000 seconds. This compares to chemical rockets with specific impulse of approximately 3000 for nuclear propulsion. This will reduce the propellant by 20 times.

6.5 TOTAL COST SAVINGS FOR A MARS MISSION

The savings for a potential Mars mission can be estimated. Savings will first be gauged in mass, then translated into budget. Savings will be primarily from propellant mass savings,

but also from power system mass savings. An estimate is based on a paper concept analysis of a Mars mission by a team from Los Alamos [Howe 1998].

The total ship mass in lower earth orbit is 582 metric tons (mT). Of this, 80% is fuel. The specific impulse of the gas core nuclear reactor is 3000 seconds, allowing a high thrust burn and therefore a shorter trip: 270 days round trip time.

Fuel mass: Applying the stable plasma thruster high specific impulse of 60,000 seconds would have a great impact on the fuel mass. The 466 mT of fuel would be reduced to 23.3 mT, a savings of 95%.

Power supply mass: The power supply on board the ship is planned to be a radioisotope supply [Difilippo 1998]. From section 3.0, a further saving of 10,600 kg is possible.

Mars ship saving: 582 mT becomes 116 mT due to the fuel savings. The additional 10.6 mT will reduce the ship mass to 105 mT; a potential saving of 82% of the planned mass.

Total mass savings: The new Mars ship in lower earth orbit would be 18% of the planned mission. In addition, the savings in launch vehicle fuel and cost will be about 50%. The combination will provide a mission mass savings of potentially 91%.

Cost savings: The cost savings will largely track mass savings. With mass savings of potentially more than 90%, cost will be reduced proportionately.

6.6 NASA THREE PILLARS FOR SUCCESS: Ten individual objectives are defined. This concept design will address one objective as follows:

Reduce the payload cost to low-Earth orbit by an order of magnitude within ten years. Stable plasma technology will help achieve this objective by reducing fuel mass to low-Earth orbit by 50%, and by reducing power supply mass.

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

1. Stable plasma technology has the potential to reduce space travel cost by more than 90%.
2. A stable plasma based jet engine will potentially reduce launch fuel costs by 50%.
3. A stable plasma based power supply for space can potentially store 10^{12} joules with specific energy of 10^{16} J/kg, compared to liquid hydrogen with 10^8 J/kg.
4. A stable plasma based space power supply will have 95% less mass than a nuclear supply.
5. A stable plasma based space propulsion system will potentially have specific impulse of more than 60,000 seconds.

Recommendations:

1. A Phase II project should be authorized to continue the concept design work as it relates to a Mars mission.

SECTION 8.0

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