A Method for the Design and Analysis of Deep-Space

Nuclear Propulsion Systems

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Abstract

While chemical rockets have been the proven workhorse of the current space industry; other advance rocket propulsion technologies have been under research and development since the advent of the space age. Among these propulsion technologies are various forms of nuclear electric and nuclear thermal propulsion systems. The goal of most of these advance rocket propulsion systems is the improved efficiency through higher exhaust velocities, while at the same time reducing the total mass of the fuel required by the rocket. These higher exhaust velocities directly affect specific impulse and thrust. Instead of the short, powerful burn and fast acceleration of chemical rockets, such advanced rockets burn for longer periods of time, providing a continuous gentle nudge that gradually builds up momentum. Systems such as these cannot be used to propel payloads from the surface of the Earth into orbit; however they provide great advantages for interplanetary flights. Since these rockets do not use chemical reactions, they only need to carry a propellant, as the need for oxidizers is eliminated. The unique advantages of nuclear propulsion systems for distant missions are explored using a Fission Fragment nuclear propulsion concept. This proposed concept is well suited for in-space travel as it provides the thermal energy required for higher specific impulses.

Nomenclature

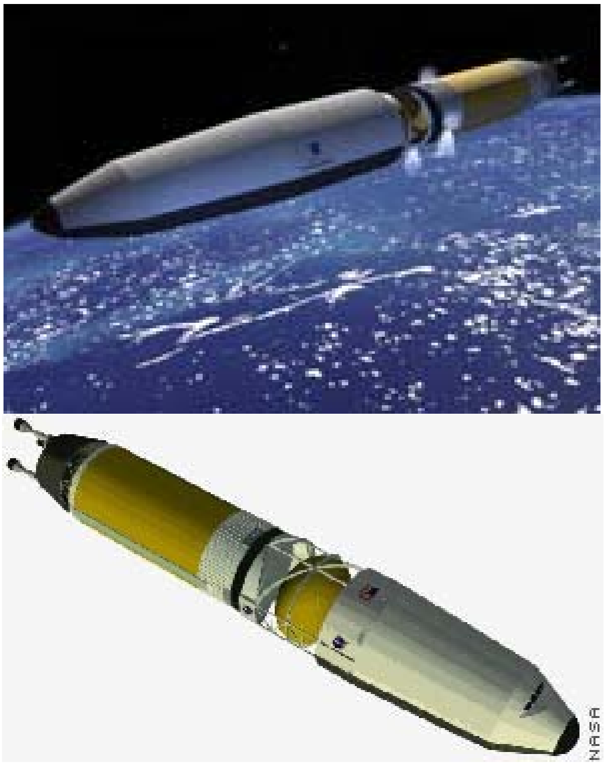
I_{sp}	Specific Impulse
F	Thrust Force
$\dot{m}_p$	Propellant mass flow rate
T	Temperature
W_{mol}	Molecular weight
A	Area
A^*	Area at the throat
M	Local Mach Number
V_{exit}	Exit Velocity
T_{exit}	Exit Temperature
M_{exit}	Exit Mach Number
R	Universal gas constant
γ	Gamma

1.0: Introduction

In January of 2004, President Bush outlined a new, bold vision for U.S. Space Exploration. The goal of this vision is to help the U.S. improve in scientific, security and economic areas. As a result, the general public has shown renewed interest in the space program, especially human exploration. Mankind has often dreamt of traveling into the space beyond the moon. Attempts to realize this dream are made as the U.S. aspires to fly manned missions to Mars, and hopefully, to the outer planets. This is a goal that began to see renewed public interest as a result of the Mars Pathfinder Mission and the 1984 discovery in Antarctica of a Martian meteorite, which hints at the possibility of fossils existing on Mars. In order to accomplish the goals of human exploration to other celestial bodies, more advanced propulsion technologies need to be further developed. In support of the Space Exploration Vision, Project Prometheus has been formed to study the application and flight of a nuclear reactor in space. This project builds on NASA’s past experience in the field of nuclear thermal rockets.

During FY93, an inter-center NASA Mars Study Team was organized by the Exploration Project Office at the Johnson Space Center (JSC) and tasked with assessing the requirements for a piloted mission to Mars as early as 2010. A mission with pre-deployed cargo was chosen as the ‘baselined concept’ and a Nuclear Thermal Rocket (NTR) propulsion system was selected for all primary propulsion maneuvers in an effort to maximize the exploration time on the Martian surface while reducing the total ‘in-space’ transit time. In FY97, NASA's Mars Human Exploration Study Team was reconvened to reevaluate, refine and update the FY93 so called ‘Design Reference Mission’ (DRM). The key mission changes to the 93-design concept included the payload manifests, and crew accommodations and consumables. In addition, significant mass reductions in many large structures, that included the propellant tanks and habitat modules, were achieved through the use of advanced composites. In fact, a lightweight, inflatable habitat module design and developed by JSC was examined.

The end results of these preliminary studies were the design requirements of the "Magnum" heavy lift vehicle or the so-called Planetary Transfer Spacecraft Concept capable of facilitating a manned mission to Mars. The Magnum spacecraft concept is called the 'Design Reference Mission' (DRM) concept for the manned exploration of Mars; this concept is illustrated in Figures 1a and 1b. To stay within the available mass and payload volume constraints required by the NASA "Magnum" heavy lift vehicle and for Trans-Mars Injection (TMI), a high performance propulsion system is absolutely essential. Further studies indicated that the Nuclear Thermal Rocket (NTR) was one of the leading propulsion options available for this spacecraft and this mission. The main reasons the NTR concept was chosen as the top contender for this mission are due mainly to its two most important characteristics; namely, its high specific impulse capability, in the Isp range of 850-1000 sec, and its attractive engine thrust-to-weight ratio, in the range of 3-10.



Figures 1a and 1b: The Magnum spacecraft concept

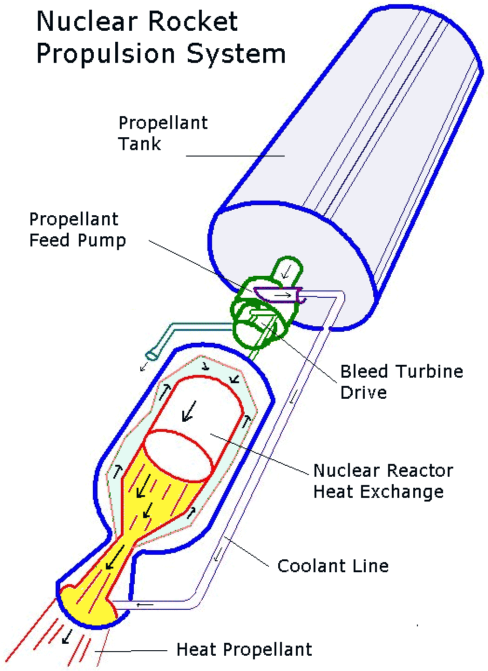


Figure 2: A Nuclear Thermal Rocket Concept

This paper describes a design and analysis concept for a Fission-Fragment (FF) Nuclear Thermal Rocket (NTR) propulsion system that is capable of supporting the Magnum spacecraft that will facilitate the human exploration of Mars. Other NTR concepts and some of their operational characteristics that can serve as possible candidate to the Magnum spacecraft are also presented.

2.0: The Nuclear Thermal Rocket Concept

Nuclear Thermal Propulsion (NTR) systems have the potential to deliver the high performance requirements for manned missions and cargo transport to the moon or Mars, unmanned explorations of the outer planets, and Earth orbit transfers of satellites. Nuclear propulsion can provide the greater specific impulse (Isp) required to reduce the travel time for manned missions to Mars from six months to about 60 days. In reducing travel time, nuclear propulsion will reduce the risk to astronauts from cosmic radiation as well as other health and psychological problems that can occur with longer mission times. In general, chemical propulsion systems can deliver an average specific impulse of about 475s, whereas nuclear thermal propulsion systems deliver specific impulses will over 900s.

The major requirements of high performance nuclear space reactors for combined power and propulsion present a unique and challenging set of engineering materials requirements. To understand these requirements, it is worthwhile to examine the factors that contribute to a rocket’s performance. Specific impulse, equation (1), is used to measure rocket performance and defined as thrust divided by propellant mass flow rate.

$$I_{sp} = \frac{F}{\dot{m}_p} \propto \sqrt{\frac{T}{W_{mol}}} \tag{1}$$

Here the symbol T represents the temperature of the reactor core and W_{mol} represents the molecular weight of propellant.

The nuclear propulsion concept of interested to this study is illustrated in Figure 2. The propellant, usually hydrogen, is stored as a liquid in an adjoining tank. The pump forces the propellant through the piping system that surrounds the nozzle and rocket motor. The propellant becomes heated and expands to a gas, at the same time lowering the temperature of the shell and nozzle. The propellant enters the reactor to be heated and accelerates out the nozzle to provide thrust. In addition, some of the heated fluid is used to turn the turbine driving the pump. Nuclear fission is an attractive possibility for spacecraft propulsion as it offers a theoretical energy density of 8 x 10^13 (in the order of 10^13) J/kg. This level of energy density is substantially higher than that of the most energetic chemical reactions, which delivers energy densities in the range of 10^7 J/kg or lower. In other words, the energy available from a unit mass of fissionable material is approximately 10 million times larger than from chemical reactions.

3.0: Spacecraft Propulsion Systems

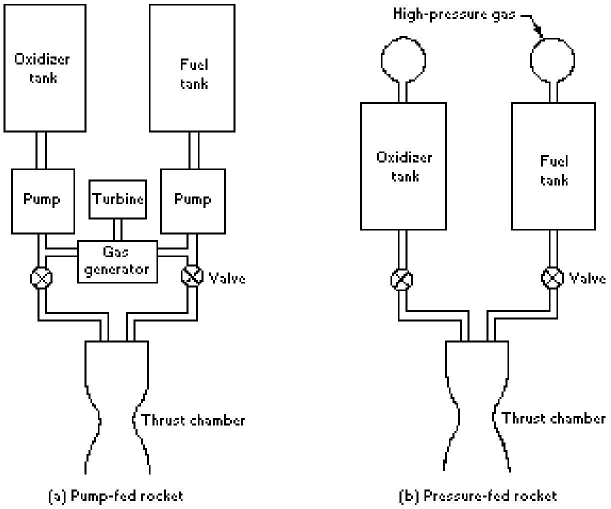
The only known way to meet the space-flight velocity requirements of the ‘Magnum spacecraft’ is through the use of a rocket in one of its several forms. Rocket thrust is the reaction force produced by expelling particles at high velocity from a nozzle opening. These expelled particles may be solid, liquid, gaseous, ions, plasma or even bundles of radiant energy. The rocket's ability to produce thrust will endure only so long as the supply of particles or working fluid holds out. Expulsion of material is the essence of the thrust production and without material to expel no thrust can be produced, regardless of how much energy is available.

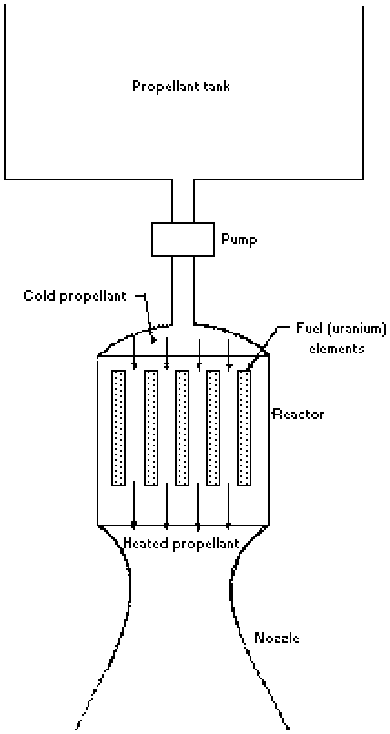
Due to this fundamental fact, a prime criterion for rating rocket performance is specific impulse, which provides an index of the efficiency with which a rocket uses its supply of propellant or working fluid for thrust production. For gaseous working fluids, specific impulse can be increased by (1) attaining higher temperatures in the combustion chamber and (2) increasing the proportion of lighter gases, preferably hydrogen, in the exhaust. The other important factor in assessing the merit of a propulsion system in a given application is the weight of the rocket and working fluid container required, as these weights influence achievable propellant fraction.

3.1: Chemical Rockets

Rockets are distinguished by the type of mechanism used to produce exhaust material. The most common example of a rocket is a compressed air bottle attached to a nozzle. The exhaust gas is stored in the same form as it appears in the exhaust. Ejection of compressed air, or other gas, from a nozzle is a perfectly satisfactory rocket operation for some purposes. The most commonly used rockets are chemical rockets in which the hot exhaust gases are produced by chemical combustion. The chemicals or propellants are of two types, a fuel and an oxidizer corresponding to gasoline and oxygen in an automobile engine. Both are required for combustion and may be in either a solid or a liquid form. The common liquid rocket is bipropellant; it uses two separate propellants, a liquid fuel and liquid oxidizer. These are contained in separate tanks and are mixed only upon injection into the combustion chamber. They may be fed to the combustion chamber by pumps or by pressure in the tanks as illustrated in Figure 3a and 3b.

Propellant flow rates must be extremely large for high-thrust rockets, often hundreds of gallons per second. Pump-fed systems may require rockets delivering several thousand horsepower to drive the pumps. This power is usually developed by a hot gas turbine, supplied from a gas generator which is actually a small combustion chamber. The pressure-feed system eliminates the need for pumps and turbines; however the high pressure, perhaps 500 pounds per square inch, required in the tanks leads to the necessity for heavier structures, thus adding dead weight to the vehicle that may offset the weight saved by removing the pumping system. On the other hand the removal of pumping equipment may raise overall safety and reliability concerns. The walls of the combustion chamber and nozzle must be protected from the extremely high gas temperature. The method most commonly used is to provide passage in the nozzle wall through which one of the propellants can be circulated. In this way the walls are cooled by the propellant, which is later burned. This technique is referred to as regenerative cooling. Thrust termination is easily accomplished with the liquid rocket by simply shutting the propellant valves; however, this operation must be precisely timed and controlled. The amount of thrust delivered can also be controlled by controlling the rate of propellant flow.





Figures 3a and 3b: Schematic of liquid-propellant rocket

Figure 4: Nuclear rocket

3.2: Nuclear Rockets

Research and development on the use of a nuclear reactor as a rocket's energy source is currently being carried out with the Magnum Spacecraft Project. The nuclear rocket does not utilize any combustion process. Rather, the hot exhaust gas is developed by passing a working fluid through a fission reactor, as illustrated in Figure 4. Liquid hydrogen is the propellant most often considered for a nuclear rocket because it yields the lightest exhaust gas possible. The hydrogen could be stored in liquid form in a single tank and forced into a reactor by a pump. After being heated in the reactor, it would be exhausted through a conventional rocket nozzle to produce thrust.

Other methods of using the fission reactor have been proposed to avoid the severe materials problem associated with the transfer of heat to the gas directly by the extremely hot reactor walls. One device would place gaseous fissile material in the center of an open reactor retaining it in position by magnetic means. Then the propellant gas would be heated by radiation from the hot gaseous fissile material without the interposition of a solid wall. The specific impulse for conventional nuclear rockets may be as high as 1200 second.

3.2.1: Solid Core Nuclear Rocket

A Nuclear Thermal Rocket (NTR) creates thrust by heating and expanding a working fluid, such as hydrogen, in a nuclear reactor. NTR's are much more efficient when compared to chemical rockets simply because the quantity of energy produced per mass fuel from nuclear reactions far exceeds that produced per mass fuel from chemical reactions. Thus, nuclear thermal rockets can produce higher specific impulses (Isp) than chemical rockets. The specific impulse of a rocket is improved by using a lower molecular weight exhaust fluid. The exhaust composition of chemical rockets is constrained by the chemical reaction. In an NTR, the heat source is not based on the propellant, thus a low molecular weight propellant, such as hydrogen, can be used to improve performance. The potential high specific impulse (Isp) levels that can be obtained from NTR's offer opportunities for missions with shorter trip times and greater payloads that those that can be accomplished using only chemical propulsion. Keep in mind that this is at the cost of an increased system weight to accommodate an NTR power plant. In this rocket the propellant is heated by a solid fuel core, resulting in rockets with specific impulse, Isp, in the range of 800secs.

3.2.2: Gas Core Nuclear Rocket

In the past, researchers at the Los Alamos National Laboratory investigated a "gas core nuclear rocket (GCNR)". In a GCNR, hydrogen is pumped into one end of a cylindrical reaction chamber, with an exhaust at the other end. The hydrogen expands as it passes through the chamber, not all of it goes out the exhaust, instead some flow back up the chamber. This creates a toroidal vortex of hydrogen gas that can be used for fission reaction containment. Dust-sized particles of uranium are injected into the toroid and accumulate at its center. A number of long cylinders are mounted on the interior of the reaction chamber outside the toroid. These cylinders normally absorb radiation emitted by the uranium, but they can be rotated to reflect it, initiating a fission reaction. The cylinders are the equivalent of control rods in an Earth-based reactor and were apparently featured in earlier NTR designs. Once fission begins in the center of the hydrogen gas toroid, the high temperatures heat the gas into plasma, which exits out the exhaust at high velocities to provide thrust. A small magnetic nozzle could be used to ensure that the uranium remains in the reaction chamber, while allowing the hydrogen plasma to escape.

GCNR was considered during the NERVA program, but the approach was clearly beyond the technology of the time. The Los Alamos studies on GCNR were theoretical and speculative, and no program to actually develop one was planned. However, the studies have shown that a GCNR rocket is much more efficient than a traditional NTR rocket. A GCNR rocket could be used to power a manned Mars mission that could reach Mars from Earth in 90 days, half the time required by a more conventional "solid core" NTR-powered vehicle. This would reduce mission cost and exposure of the crew to radiation. In a GCNR no longer is there concern about the fissionable material vaporizing, as in this system the propellant fluid is passed through a fissioning plasma, thus allowing the highest possible core temperature (apart from antimatter). With a cooling system the specific impulse can be as high as 7000secs.

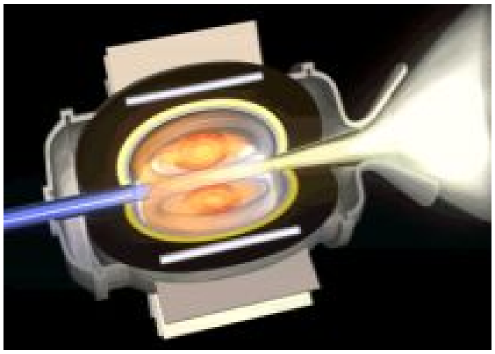


Figure 5: A Gas Core Nuclear Reactor

4.0: Justification for Nuclear Thermal Rockets

The idea of using nuclear power as the basis for a rocket predates the First World War. However, at that time neither liquid rockets nor atomic power were realities, as such in those days these concepts were highly speculative. At the end of World War II, both large liquid-fuel rockets and atomic reactors were working technologies. In 1946, Douglas Aircraft performed the first formal study of the use of nuclear power for rocket propulsion. This concept for space propulsion experienced tremendous growth in the 1950s and into the 1960s. Unfortunately, in the 1970's with the rise of the 'environmentally righteous class', nuclear technology was viewed as a tremendously powerful and equally uncontrollable force that poses grave safety concerns. Scientists were encouraged to seek alternative means of propulsion, and the nuclear rocket system was placed on hold for three decades.

Technical reviews conducted in 1990 showed that the United States space program relied heavily on lightweight batteries, fuel cells, and solar modules that provided electric power for space missions. As missions became more ambitious and complex, power needs increased. Scientists investigated various options to meet these challenging power requirements and concluded that one of the best options available is nuclear energy.

Today, nuclear powered spacecrafts are exploring the outer planets of the solar system and orbiting the sun and Earth. Some have landed on Mars and the moon. They provide the power that enables us to see and learn about distant objects within our solar system. Thanks to the use of nuclear propulsion systems, reliable sources of power were provided to spacecraft during the exploration of Jupiter, illustrated in Figure 6, and it’s four major Jovian moons; namely, Io, Europa, Ganymede and Callisto. Without a reliable source of power to meet the needs of the Galileo spacecraft's (see Figure 6) it’s mission would not have been successful.

5.0: Current Nuclear Power Systems in Space

Scientific instruments and electronic, photographic, and communication equipment are the heart of exploratory missions because they collect the data and transmit it back to Earth. Without the technology to reliably power these instruments in space, our knowledge of the solar system would be only a fraction of what it is today. In fact, the requirements for power in space are highly specialized. The weight and volume of hardware launched into space are carefully considered, including all power sources. The generator must meet mission power requirements, as well as weight and space limitations. Safety is still a prime consideration in the use of nuclear propulsion, because of the hazards associated with launch, re-entry, and other mission activities.

Today, the success of the Cassini mission, as illustrated in Figure 7, is among our best example in the use of nuclear power for space exploration. The October 1997 mission is a joint U.S.-European venture to explore Saturn in great detail; a journey that will take nearly seven years. Like Galileo, Cassini used gravity-assists from other planets to achieve the necessary speed to reach Saturn. Cassini employed four flybys: two by Venus, one by Earth, and one by Jupiter, to reach its destination in deep space. Plans are for the Cassini orbiter to explore the Saturnian system for nearly four years, flying some 60 orbits of the giant planet during that time. The electrical energy to power Cassini's mission equipment, including all its communications and scientific sensors, will come from a nuclear propulsion system that is capable of providing a total of 850 watts of power.

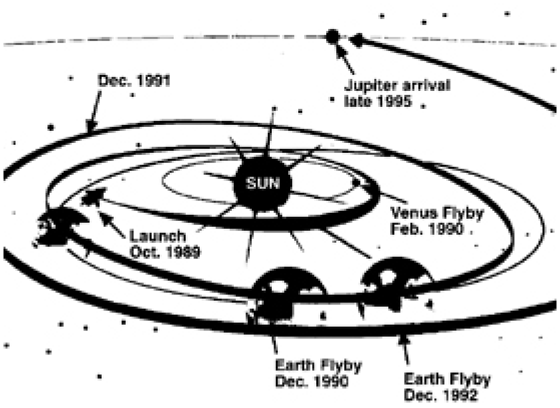


Figure 6: Galileo Trajectory to Jupiter

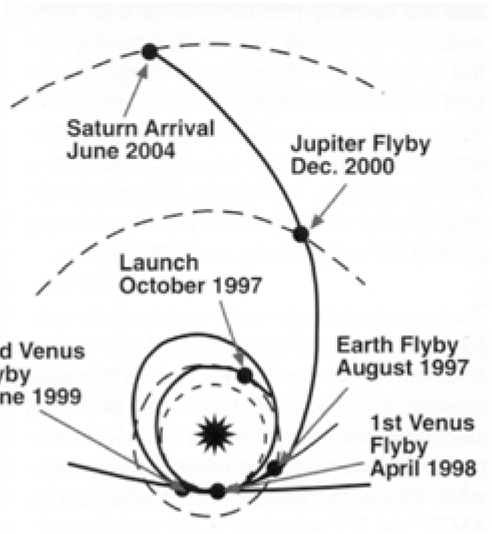


Figure 7: Cassini Trajectory to Saturn

6.0: Future Space Systems Requirements

The rebirth of a 50-year old idea that has never had an opportunity to prove itself was announced as part of the U.S. President’s vision of space exploration. The Jupiter Icy Moons Mission (JIMO) is finally up for serious considerations. This type of space exploration project has the potential to place nuclear propulsion and power systems in its rightful place in the arsenal of tools that the space designer must work with. In fact, the JIMO mission is recast as ‘Project Prometheus’ which will involve the exploration of the Moon and Mars. In addition, the European Space Agency (ESA) and NASA have identified a number of potential missions that can best or only be undertaken using nuclear sources for power. However, these future missions depend upon two important conditions: First, there must be a reliable and continuing supply of Pu-238 fuel from the US Department of Energy. The US facilities that could supply Pu-238 are being considered, as are foreign sources such as Russia, England, and France. Second, smaller and more efficient power systems will have to be developed consistent with NASA's needs.

Currently, the principal distinctions between categories of space propulsion systems are related to whether significant gravitational fields are involved. Leaving a gravitational field requires a high thrust propulsive system. Orbit-to-orbit trips can be made with fairly low thrust, though such trips take longer and are less efficient because gravity reduces effective thrust. If a planet has an atmosphere, atmospheric drag (aerobraking) can be used to offset requirements for inbound propulsion. Because of differences in mission duration and in the accelerations achievable using various techniques, some transportation modes are more relevant to manned flights and others to cargo flights. Manned flights require fast and safe transportation to minimize life support requirements and radiation exposure. Cargo flights can be slower.

The current U.S. effort to develop nuclear reactors for space is centered in a program entitled “SP-100," which is a joint program of the Department of Defense, the Department of Energy, and NASA. The policy of the United States for all U.S. nuclear power sources used in space is to ensure that the probability of release of radioactive materials and the amounts released are such that an undue risk is not presented, considering the benefits of the mission (U.S. Department of Energy 1982). Safety criteria are specified for the design of the SP-100 space nuclear reactor power plant; safety is to be built into the design, not just added on. Space nuclear power applications must keep the radiation exposure of astronauts, occupational workers (e.g., ground support personnel), and members of the general public "as low as reasonably achievable" during all mission phases, normal and abnormal.

In the near future, a stepwise development is envisioned in all areas of space propulsion and power sources. Nevertheless, it should be noted that the development of the 1-10 MW class of nuclear power systems will have a profound influence on the state and direction of the electric propulsion programs. In addition, power levels in the range of 1-10 MW will enable electrically propelled orbital transfer vehicles and interplanetary explorers to travel to the outermost fringes of the solar system with larger payloads and shorter trip times than chemical systems. In view of these potentialities, a strong emphasis on developing such propulsion systems is warranted.

7.0: Mars Space Systems Requirements

The basic criteria for a propulsion system to be employed in the future exploration of Mars are:

- the technology employed should be a mature and flight-tested
- the reliability of the engine must be of a high degree to assure maximum safety of the crew
- efficiency must allow for a sizable payload, a modest Earth-to-orbit mass, a short travel time, flexibility in selection of the mission parameters, flight plan changes during flight, ample accommodations for the crew, and opportunities for scientific observations and
- in the case of a nuclear system, the operation and testing of the reactor should not present an undue hazard or a cause for concern on Earth and in space.

In addition, there are many technological obstacles that need to be overcome to make the human exploration of Mars and the other planets in our solar system a reality. One of the main obstacles is the development of an efficient and safe propulsion system. Because of the very large distances involved, the need to reduce the mission duration for medical concerns, and the weight limitations imposed by the existence of a manned crew and their life support system, the propulsion system chosen must be fast, cost-efficient and as safe as possible.

8.0: Material Considerations for Nuclear Powered Spacecraft Rockets

The materials used in the construction of rocket boosters and space vehicles range from special high-density material for heat absorption to high-strength, lightweight materials to carry flight loads. For each application, the requirement for minimum weight is dominant. Any unnecessary pound of material used in the construction of the flight vehicles reduces the useful payload by at least 1 pound.

At present, designers have achieved structural configurations which have more than two-thirds of the maximum possible strength per pound of material. Some further gain can yet be expected from novel designs, closer control of material properties and manufacturing tolerances, and the use of very large single shapes. Today's most efficient structural materials for normal temperatures, such as aluminum and titanium, can be surpassed in the future by new materials such as beryllium and composite materials using high-strength filaments.

The best current high-temperature metals, e. g., nickel and ferrous alloys, may soon be replaced by molybdenum. A better future prospect for higher temperatures is tungsten; however, currently there is little metallurgical work being done on tungsten, and no effort toward alleviating such problems as its affinity for oxygen. Another excellent prospect for high-temperature use is carbon, possessing a host of attractive properties. The structural use of carbon will be severely restricted by its brittle behavior and the need for protection against oxidation, hydrogenation, and nitrogenation, problems on which little research is being done at present.

Ceramics such as carbides have very high melting points and show much promise for high-temperature use. They do not exhibit any ductile behavior, except in a few rare cases under meticulously controlled surface conditions; but they remain an attractive field of investigation. Since various materials demonstrates individual strengths, (for example, tungsten's ductility, ceramics' high-temperature strength); the ideal material would be a composite of two or more materials, each component being utilized only for its best property. In some applications it may be advantageous to protect conventional structures from severe thermal environment, rather than to make a structure of high-temperature materials. Relatively brief encounters with a hot environment can be survived by the protection method, as in the insulation of rocket nozzles and reentry nose cones.

9.0: Structural Considerations for Spacecraft Designs

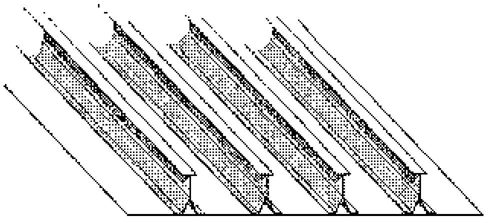


Figure 8: Sheet stringer construction

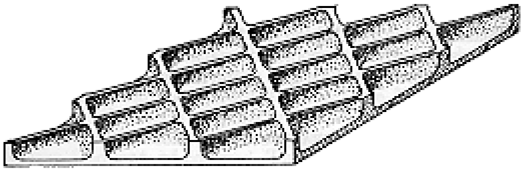


Figure 9 Waffle construction

In attempting to reduce weight, the rocket and in general the vehicle skin thickness must be as thin as possible. Since very thin sections of material possess appreciable strength only under tension loads, many unique design and handling problems are created whenever such thin sections are used. Therefore, there is a need to study and conduct experimentation on such spacecraft designs.

Currently, there are several methods for using thin-walled structures. In some cases the structure can be internally pressurized to keep the walls from buckling. The net stretching force due to internal pressure is made greater than the compressional force due to flight loads. Another method of stabilizing thin sheets is commonly used in the construction of conventional aircraft, refer to Figure 8. In this case, the sheets and the stiffening members or stringers are fastened to the skin in the direction of the compressive load.

The same results can be obtained in a single piece by chemical milling or machining of a solid sheet to remove all metal except ribs or "waffles" that act as stringers, refer to Figure 9. Thin sheets can also be stabilized against buckling by placing a lightweight supporting core between two sheets to form a "sandwich." The core might be in the form of honeycomb as illustrated in Figure 10. Corrugation, light plastic and metal foam sandwich constructions are becoming increasingly important in higher temperature applications. These types of construction methods have already been used in hypersonic vehicles designs.

10.0: Space Structures

A number of space-flight applications require specialized applications. For example, the collection of solar cell panels for power generation, involve very large structures; covering areas of millions of square feet in extreme cases. The weight of these structures must be kept very low in order to make the associated systems feasible. In addition to the problems of operating such structures in space are the problems of packaging extensive amounts of fragile material compactly for carriage on launching rockets. This section highlights some of the specialized structural problems associated with space travel.

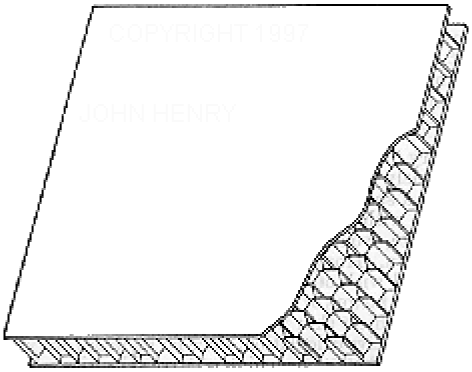


Fig. 10: Hexagonal cell core sandwich panel

10.1: Structural Dynamic Problems

The bending and vibration of very light rocket structures interact with the flight-control system to such an extent that the structure and control system must be approached as an integrated design problem.

10.2: Temperature Control

The equilibrium temperature of a spacecraft is determined principally by the nature of the structural surface. The radiation properties of this overall surface determine the relative rates of absorption of solar energy by the vehicle and the radiation of vehicle heat into space. This balance, along with the quantity of heat generated internally determines vehicle temperature. Measures available to adjust this temperature balance include choice of surface color and smoothness of finish, as was done in the case of Explorer and Pioneer. In addition, the overall surface characteristics may also be controlled in flight by operating "flaps" that cover or expose more or less surface area, a technique that was implemented on Sputnik III.

10.3: Meteorite Hazard

The depth of vehicle skin penetration due to meteoroid impact is a somewhat speculative calculation, since no facilities are yet available for experiment on effects at such high relative velocities. The combination of great uncertainties in number and size of meteorites, in relative velocities, and in the phenomenology of high-speed impact, lead to widely uncertain estimates of the hazard to space vehicles due to meteoritic matter.

10.4: Multipurpose Structures

Due to the great premium on weight reduction in a space vehicle, designs that use a single item of structure for more than one purpose would be highly desirable. It has even been suggested that material for propellant tankage, can potentially be made up of combustible material, such as lithium, and that material might eventually be used as fuel after it has completed is primary design purpose.

10.5: Additional Areas of Investigation

Other areas in which important uncertainties still exist include the effects of various materials due to prolonged exposure in total vacuum. Of particular importance is the effect that such exposure has on critical surfaces that relies on the benefits of lubricants and paints. In addition, the behaviors of containers of gases and fluids under a combination of prolonged exposure to radiations in a vacuum are still a mystery.

11.0: Nuclear Fission

Nuclear fission is the splitting of an atom into several smaller fragments, as illustrated in Figure 11. This is induced by bombarding an atom of fuel; uranium-23, plutonium-239, uranium-233, or possibly thorium-232, with neutrons, also illustrated in Figure 11. The fissionable atom then captures the neutron and splits or decays into two smaller atoms or isotopes; such as, iodine-131, caesium-137 or strontium 90, and two or three neutrons. These neutrons go on to split other fissionable nuclei resulting in a chain reaction. The combined weight of the fission products is less than the weight of the original nucleus. The loss of mass is on the order of 0.1% of the original fuel mass, which due to Einstein's mass energy relationship; $E = mc^2$, is converted into the massive energy output of the reaction. Nevertheless, there are many engineering problems associated with this technique, standing out among them the issue of safety. The products of the fission are all highly radioactive and the process itself results in a substantial amount of both beta and gamma radiation.

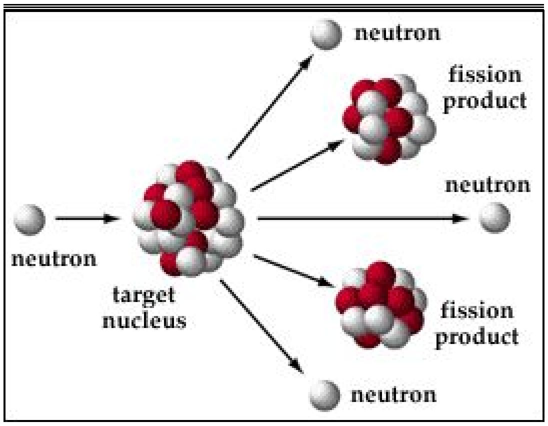


Figure 11: Illustration of the Fission Process

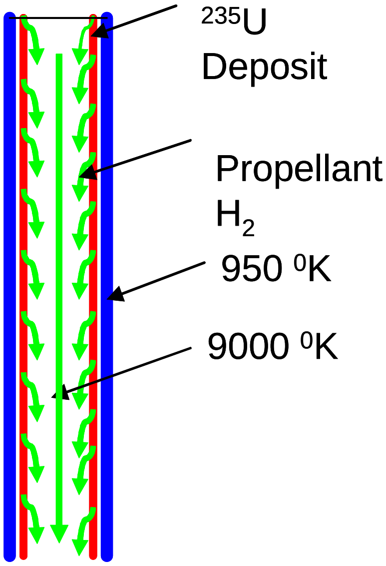


Figure 12: Structure of a single tube

11.1: Nuclear Fission Fragment

The proposed fragment fission propulsion system design for this study involves fission fragments heating a secondary fluid. Conceptually this system comprises of a hollow perforated tube whose inner walls are lined with a very thin layer of nuclear fuel. This layer is on the order of approximately three micrometers and enables the fragments once produced to easily escape. Fission reactions occur within this layer and some of the fragments produced flow out of the inner wall and moves towards the central region of the tube. In moving from the inner tube layer to the central region the fission fragments come into contact with the propellant gas that entered the tube through the tube's perforated walls. These collisions result in the fission fragments transferring their kinetic energy to the propellant gas molecules. This has the effect of increasing the net internal energy of the propellant gas molecules to the extent that dissociation of the propellant gas molecules can occur.

Temperature in this central region rises above 9000 ^oK. A percentage of the fission fragments produced collide with the walls of the tube imparting their kinetic energy to the tube walls. The entire tube is surrounded with a liquid metal bath, lithium, which is used to keep the tube walls cool. Temperature at the tube wall is projected to be around 950 ^oK , which is well within the structural integrity of materials available today. The excess heat removed by the liquid metal can be used to generate power for secondary systems on board the vehicle or it can be radiated out into space. Figure 12 illustrates the structure of a single tube. The physical dimensions of the tube are chosen such that the reactor can be transported within the cargo bay of the space shuttle. It is estimated that 87 N of thrust can be generated by a single tube. Therefore, it stands to reason that an arrangement of tubes will result in a total thrust that is directly proportional to the number of tubes in the arrangement. It also stands to reason that the complexity of the system increases with each arrangement. n nature and man-made systems it has been proven that to achieve the maximum use of limited space objects need to be packed in a hexagonal manner. This results in an arrangement as illustrated in Figure 13 for a 37 tube arrangement. In this horizontal slice of the conceptual reactor we can see the locations of some of the other major components.

A vertical slice of the conceptual reactor is illustrated in Figure 14. Essentially this a collection of these tubes, control rods, supply and removal pipes for the coolant, and supply pipes for the propellant. The tubes are surrounded by the liquid metal bath which is housed within the diffuser moderator. Also housed within the diffuser moderator are the control rods.

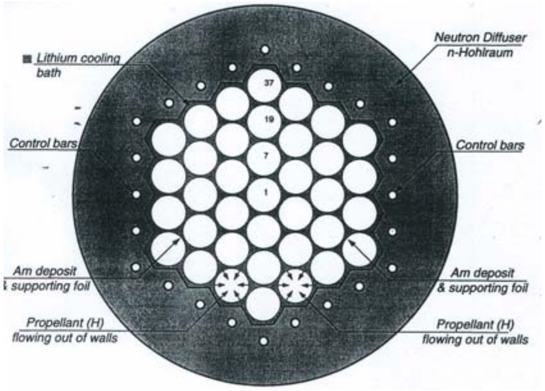


Figure 13: Illustration of FF tube packing

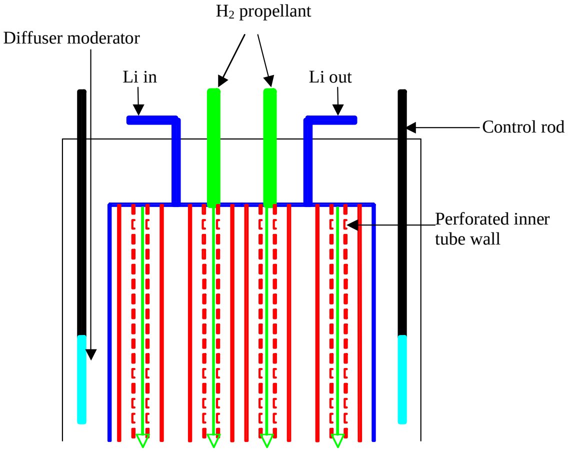


Figure 14: Vertical slice of reactor

11.2: Fission Fragment Rocket Nozzle Design

The Quasi-one Dimensional principle is used in the design of the rocket nozzle which is illustrated in Figure 15. The super hot hydrogen flow leaves the Fission-Fragment (FF) tubes and is processed in a convergent-divergent nozzle as shown in Figure 15. The flow-field variables are assumed to vary in one direction only. As illustrated in Figure 15, the cross-sectional area, pressure, density, temperature and velocity are all variables in one direction, x. Having increased the internal energy of the propellant gas, H_2, to an extremely high temperature in the FF tubes, the convergent-divergent nozzle is now required to effectively and efficiently convert this internal energy to kinetic energy, and thus deliver the much needed thrust. Further, it can be demonstrated that if the cross-sectional area at any point in the convergent-divergent nozzle is known, then the local Mach number at that point can be evaluated from the following relationship;

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/(\gamma-1)} \qquad (2)$$

where the symbol, M, represents the local Mach number in the nozzle.

Once this parameter is determined, the exit velocity at the rocket nozzle can be evaluate using the expression;

$$\begin{aligned} v_{exit} &= M_{exit}\sqrt{\gamma \Re T_{exit}} \\ T_{exit} &= F(M_{exit}) \end{aligned} \qquad (3)$$

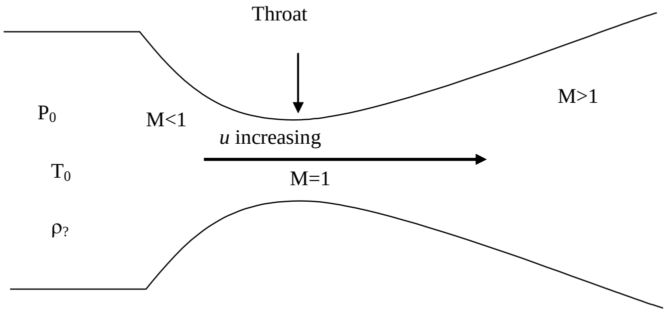


Figure 15: Illustration of the conversion of internal energy to kinetic energy using the Quasi1D nozzle

Having constructed the nozzle, the rocket can be assembled as illustrated in Figure 16 and a detailed performance analysis conducted.

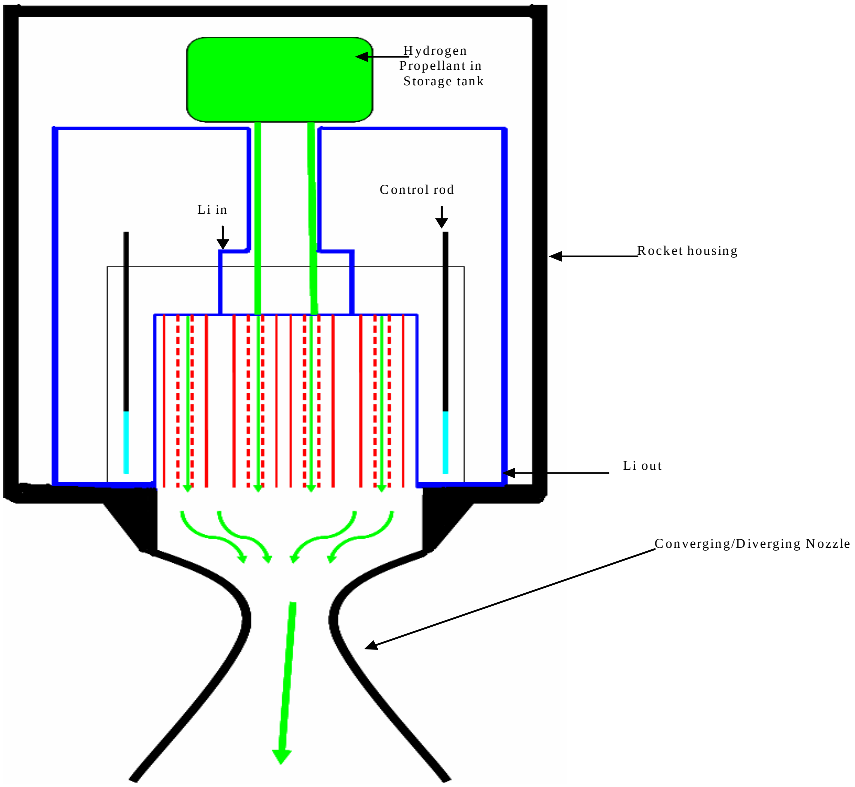


Figure 16: Illustration of complete basic Fission-Fragment rocket.

12.0: Results and Analysis

Table I compares the proposed FF concept and the Nuclear Engine for Rocket Vehicle Application (NERVA) concept. Clearly the FF concept out performs the NERVA concept, theoretically.

Table I. Performance Analysis of the FF concept and the NERVA project.

	p	h	T	I_{sp}	V_{EXIT}	M_p/M_{final}	M_p/M_{final}
Unit	bar	MJ/kg	K	sec	km/s		
FF	1.5	200	> 3000	> 900	> 9	4.3	1.1
NERVA	50	50	3000	900	9	15.1 ΔV =25km/s	2.4 ΔV = 11 km/s

12.1: Potential Mission Using the FF concept to support the Magnum spacecraft.

The FF reactor concept could be incorporated in the NTR rocket design supporting the Magnum spacecraft for a potential point and shoot mission to Mars. The point and shoot mission will entail a round trip time to the red planet, inclusive of stays of 30 to 90 days, of about nine months. This particular type of mission occurs in four stages, all requiring high change in velocity (ΔV) burns. The Trans-Mars Injection (TMI), Mars Orbital Insertion (MOI), Trans-Earth (TEI), and Earth Orbital Insertion (EOI) staging points require ΔV burns in the order of 6.4, 12.3, 15.3 and 14.7 km/s respectfully if the mission occurred in 2011. Both the FF and the NERVA concepts can provide these large ΔV's; however the FF concept provides a much more attractive M_p/M_{final} ratio.

12.2: Simple design Parameters for a Nuclear Fission-Fragment Rocket

Table II provides some simple general design parameters for a FF rocket. The independent inputs, material properties, and structural arrangement are all baselines and subjected to changes as research is done on the FF rocket concept. Figures 17-19 illustrates the initial investigation of various basic parameters.

Table II: Nuclear Fission Fragment Rocket Sample Design Parameters

Description/Type	FF Chamber	Reactor	Nozzle
Independent Input	Radius	Number and Arrangements	Geometry
Material Properties	^{235}U	Coolant, Li	Propellant, H_2
Structural	Wall Thickness & Composition	Wall Thickness & Composition	Wall Thickness &Composition

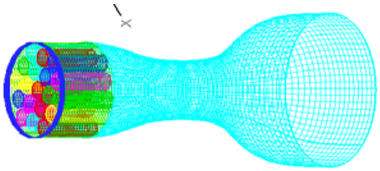


Figure 17: Geometric construction of FF reactor and nozzle.

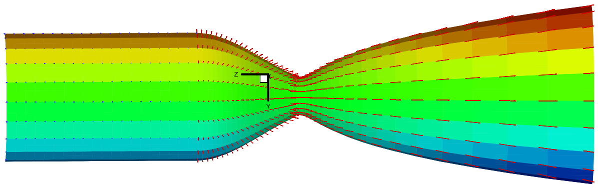


Figure 18: Flow variables.

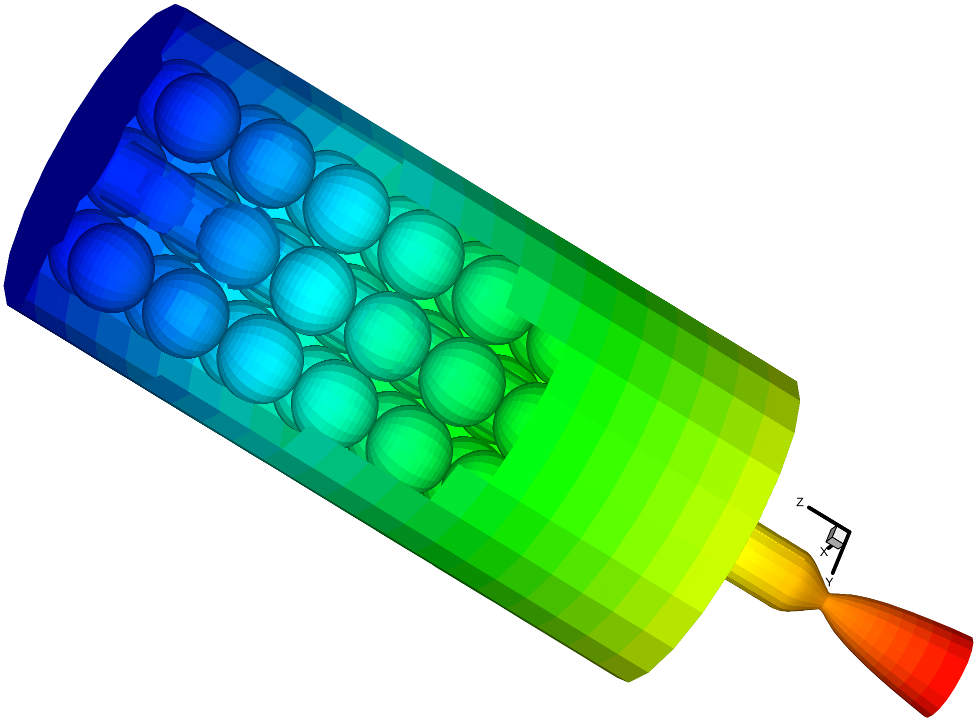


Figure 19: Proposed propellant storage configuration for an FF rocket.

13.0: Conclusion

Chemical rockets have been an integral part of the space industry; however they are not very efficient when it comes to in-space human missions. Unlike the Apollo lunar missions, the distance to Mars and other planetary bodies within our solar systems are much greater. Human missions to these planetary bodies, inclusive of Mars, require propulsion systems capable of reducing the round trip time, making the time away from Earth as short as possible. This requirement is essential to ensure the safety of a human crew, both physically and psychologically. Nuclear powered spacecrafts can make these missions a reality. Current technology can support fission reactors in space. Fission reactions are currently the only practical reactions that can deliver the quantity of energy required per unit mass. This quantity of energy is required to provide the increase in the range of specific impulse and thrust, making human missions possible. Fission reactors, weather solid core, gas core, or fission fragments, provides the safest means to open up our solar system to human exploration.

14.0: Acknowledgments

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