High Energy Density Propulsion –

Reducing the Risk to Humans in Planetary Exploration

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Abstract

The potential benefits to humankind of space exploration are tremendous. Space is not only the final frontier but is also the next marketplace. The orbital space above Earth offers tremendous opportunities for both strategic assets and commercial development. The critical obstacle retarding the use of the space around the Earth is the lack of low cost access to orbit. Further out, the next giant leap for mankind will be the human exploration of Mars. Almost certainly within the next thirty years, a human crew will brave the isolation, the radiation, and the lack of gravity to walk on and explore the Red planet. Both of these missions will change the outlook and perspective of every human being on the planet. However, these missions are expensive and extremely difficult. Chemical propulsion has demonstrated an inability to achieve orbit cheaply and is a very high-risk option to accomplish the Mars mission. An alternative solution is to develop a high performance propulsion system. Nuclear propulsion has the potential to be such a system. The question will be whether humanity is willing to take on the challenge.

Keywords: nuclear propulsion, nuclear rocket, Mars mission, access to space

Risk versus Benefit

Risk. How do we gauge risk…to a country…or to a civilization. At what point do the benefits offered by an action outweigh the perceived risk? Here, “perceived” is the operative term. Risk is estimated -- the true risk is never known until the adventure is complete. So the actual risk is a guess held in the minds of those who, more often than not, are not involved in the action.

If humanity is to explore the universe, we must overcome the obstacles presented by those who would prevent us from taking even the first step because of the perceived risk. Exploration is a risky business. Explorers will die in lonely places. Fortunes will be lost – and made. Therein lies the rub—what are the benefits? Why should a country risk anything to explore space? Why not fix the problems on Earth first before we go traipsing around the solar system?

To go or to stay? This question has divided humans for centuries. Humans seem to be split into those who would stay at home to fix humanity’s problems and those that simply have to see what lies beyond the next hill ... and the next. For those who wish to stay and wait, they must consider the possibility that the social problems are never ending – that at no point in the future will the problems at home ever be considered to be solved. They must consider the possibility that all animals held in a closed ecosystem will not reach a steady-state, balanced, in-tune-with–nature existence but instead will find that their populations will increase, resources will deplete, wars will be fought, and poverty will always be with us.

In fact, the stay-at-homes must even consider that the staying-at-home <u>is</u> the problem. The lack of a frontier, of an open expanse to explore, is to a civilization what a cage is to a wild animal. In truth, the ability to explore unknown places may, in fact, cure far more of society's ills than government programs and huge dumps of money. Who can argue against the impact on the world's population of having a bright point of light up on the Moon's surface each night where humans work to uncover the mysteries of nature? A place where Earthmen work -- not Americans, nor Russians, nor Christians nor Muslims -- just Earthmen. What impact will such a sight have on children all over the world?

The one major difference between exploration of space and that on Earth is distance. Everything is just so far away. Yes, the moon is only three days away, but the next step after that is huge. Using current rockets, a trip to Mars is around six months. Imagine six months trapped in a can. The human psychology will be strained not only because of the confinement but because of the ever-present knowledge that you simply can't go home -- even in a life or death emergency. In fact, because of planetary motions, you can't get home for three years. Three years of close quarters, tiresome crewmates, broken equipment, sores from your spacesuit, and always, continually, the ever present bombardment by cosmic rays blasting your cells every second.

In the past, adventurous crews explored the Earth in slow moving ships. Rarely, though, was any vessel at sea very far from land longer than three months. Those hearty adventurers were tough seasoned sailors yet they had the advantage of breathing air on deck, of feeling the wind in their face, and of finding fresh supplies at each port. In space, the crew must carry everything it needs—all of it. A three year mission of this type seems ludicrous to consider.

The answer, of course, is the same answer that has sprung forth throughout history. We simply need to build ships that go faster. Reduce the trip time to a year and any crew can fulfill the mission with a good chance of coming home. Going faster will reduce the risk.

The technology for a new type of rocket that would enable fast missions to outer planets was developed in the 1960’s by the Los Alamos Scientific Laboratory. Originally pursued to be used for ICBMs, rocket engines based on fission energy were designed, built, and tested in the Rover/NERVA programs. In all, over 23 different designs were tested between 1955 and 1971. The performance of the engines was about twice that of the current engines used on the space shuttle. So why weren’t these engines used? In 1952, Dr. Werner von Braun and others [1,2] theorized that humans would be on Mars by the mid- 1970s. NERVA rockets could get to the Moon in a day -- to Mars in four months. Why aren’t we already on the Moon and Mars?

Is it because of the perceived risk of fission energy?

Perspective

The "N" word

For several decades now, the public has been told to fear the use of nuclear power. Today at NASA research centers around the US, nuclear is referred to as "the N-word" as if to say the whole word will bring doom upon the speaker. The public around the world has been indoctrinated that nuclear energy and, in fact, radiation in general is an evil. Yet this is totally untrue. One third of all patients admitted to hospitals in the US receive treatments involving a radioactive agent [3]. Nuclear power in the US has proven to be the cleanest source of energy from an environmental impact perspective – no tons of radioactive ash from coal and no tons of carbon dioxide and other acidic pollutants from oil or gas -- just lots of energy from small quantities of material. In fact, the energy contained in a kilogram of uranium is equal to that in 40 million kilograms of natural gas. It is this feature of high energy-density, i.e. energy per unit mass, that makes nuclear energy the best candidate for propelling the human presence into the solar system.

Clearly, there is risk associated with using nuclear energy. That's the point in one respect – have we learned the ability to control the use of a high energy-density source safely? No one can dispute the impact of Chernobyl. But the lesson to be learned is not to ban nuclear power but to be certain the reactor design is safe. Several countries have proven that good reactor designs are possible. Even Three Mile Island, riddled as it was with human error, still prevented major loss of any radioactivity to the local environment. Nuclear power has proven to be the most reliable and environmentally friendly source of electrical power ever developed. Humanity has, in fact, learned how to control this energy source.

The main objection to using nuclear power for domestic energy production is storing the radioactive waste for long times. Other countries have solved this problem by reprocessing the material and extracting valuable radioisotopes for medical and industrial applications. The US has chosen to demonstrate a woeful lack of vision and simply ignore the problem. Regardless, in space, the problem is non-existent. While in operation, the waste is retained in the engine’s core where shielding protects any nearby human activities. Near the end of the lifetime of a nuclear rocket, the unit can be safely deposited into a very high orbit with a lifetime of a hundred thousand years.

Space is vast -- that’s all there is to it. Interplanetary distances are on the scale of hundreds of millions of miles. Mars at closest approach is two hundred times farther away than the Moon. Pluto at closet approach to Earth is six billion miles away! Travelling such distances, even to get to Mars, in a reasonable time frame implies the need for high speeds. High speed means energy. The higher the energy content per pound of ship translates directly into a faster trip.

Clearly unmanned probes can be sent out to explore the solar system. The Cassini probe, launched in 1997, just passed the halfway point to its final destination. Almost forgotten by the public already, the satellite will need seven years to get to Saturn because of the chemical propulsion used in the mission. A small nuclear reactor making electricity for ion thrusters such as those tested on NASA's Deep Space 1 mission could have had the probe there in less than three years for the same initial mass in orbit, i.e. the same launch cost. In addition, the Cassini probe used a Radioisotope Thermoelectric Generator (RTG). An RTG is a lump of plutonium that heats up by radioactive decay. To produce electricity for the probe the RTG had an activity of 400,000 curies. A nuclear reactor prior to operation, because it is initially just uranium with no fission products, would have an activity of perhaps 0.5 curies – almost one million times less.

Technical versus Social

The use of nuclear power in space boils down to issues in two separate areas: technical and social. The social impediments are subjective, emotional and often, ill-informed. Many special interest groups, often claiming to be pro-environment, have established themselves as anti-nuclear. In most cases, this categorical stance extends to the use of nuclear energy in space. The acceptance of this position by the public has hamstrung the US planetary exploration program. Waiting seven years to get your data is no way to carry out an experiment. In order for humanity to progress into space, this author believes that we will have to accept the use of high energy-density sources such as fission. In fact, history often characterizes past civilizations by the magnitude of the energies they harnessed -- wood fires, coal fires, coke fires, and combustion of oil. Currently, we have reached the end of the chemical energy ladder with the combustion of hydrogen. Very likely, we will be judged by future historians by our ability to accept the challenge and demands presented by the use of nuclear power.

The fears invoked by the perceived risk are unreasonable. According to the WASH 1400 report, the risk of all the nuclear power plants in the US causing ten deaths is 100,000 times LESS than having ten people killed in an airplane crash. It's even 1000 times less than the chance of ten people dying from dam failures. Letting fear of a technology rule the course of history of a civilization is an irrational path. We can easily imagine early man finding a flaming branch after a lightning storm. Upon returning to his lair to show the new light to his tribe, he accidentally burns his finger, drops the branch and sets fire to skins, bedding and surrounding detritus. The conclusions by the tribe: the flame is bad, evil; Put it away; Hide in the dark. But those who choose to conquer their fears will progress. Those who run and hide in the dark will not.

Nuclear rockets can be operated cleanly and safely. The waste produced will be held within the material of the core. No radioactivity will enter the Earth's biosphere. With suitably designed shielding, a human crew will receive a radiation dose less than five percent above that occurring naturally on a journey in space. Space is a vacuum but it is not empty. Intense levels of high energy radiation fill the void. Ironically, therefore, because the trip time would be shorter, the human crew would actually receive a smaller radiation dose on a mission with a nuclear rocket than a mission with a chemical propulsion system.

Technical Issues of a Fission Rocket

From a purely technical standpoint the fission rocket has inherent advantages. Fundamentally, a nuclear rocket is just a simple heat exchanger, much like the burner on a stove. In essence, uranium particles are mixed into a block of graphite that has many parallel holes passing down the length. Using surrounding control rods, the block is made to produce fission energy which heats it up to very high temperatures. Hydrogen from an external tank flows into the block, through the holes, and is heated to high temperature and pressure. The hydrogen is then exhausted out the nozzle at high speed.

The nuclear engine is a simpler system than the main engines on the space shuttle. The chamber pressures are lower, the operating temperature is lower in the chamber, only one set of turbopumps is needed for the hydrogen, and there is no “barely contained” explosion. In addition, because there is no liquid oxygen tank, the chance of a Challenger-type explosion is reduced to near zero.

In short, the advantages of a fission powered propulsion system are:

- that a fission rocket can be built that will retain all of the radioactive by-products within the core,
- that the rocket can have a clean exhaust with no entrained radioactivity,
- that prior to operation the rocket is almost non-radioactive,
- that the rocket engine has around two times the performance of the best chemical engines yet developed, and
- that a fission-based engine can enable short transit times to the Moon, Mars, or even the farther planets and thus reduce the risk to the crew.

Either we will eventually overcome the social resistance through education of the public or we will fail to send humans to nearby planets. The social issues raised by opponents are often shadowy, fluid, and hard to succinctly define. The technical issues, though, can be addressed and identified.

History of the Nuclear Rocket

In 1955, the Los Alamos Scientific Laboratory began the Rover pr a solid core nuclear rocket engine. The basic concept was to all nuclear reactor to reach high temperatures, cool the reactor wi exhaust the high speed hydrogen for thrust. The expected advantage shorter trip times, lower mass in orbit, and no possibility of ac

In 1963, the Nuclear Engine for Rocket Vehicle Applications (NER the Aerojet Corporation as the prime contractor and Los Alamos contributor. The goal of the NERVA program was to transform t technology developed by Los Alamos and produce a space qualified Figure 1. Both Rover and NERVA were terminated in 1972 when the

decided to cancel any plans for sending humans to Mars. Before the Rover/NERVA programs achieved the following:

- built and tested 23 reactors/engines,
- achieved fuel temperatures in excess of 5500 degrees F,
- ran a reactor with a peak power of greater than 4000 megawat
- operated a system for over an hour,
- demonstrated multiple start-up and shut-down operations, and

- proved that the graphite based reactor core could withs conditions of operation.

Figure 1. Photograph of the NRX engine being transported to Test Rocket Development Station at the Nevada Test Site.

All told, from 1955 to 1971, the US spent around $3.5 billion (1960 $) to design, build, and test nuclear rockets. Three different test cells were used. The final test facility, the Engine Test Stand, enabled integration of the hydrogen turbopumps into a vertical test firing operation as seen in Figure 2. In addition, two assembly/disassembly building were constructed that allowed "hot" engines to be totally dismantled after firing. These facilities were critical in discovering the weaknesses in the early reactor designs.

Figure 2. Photograph of the XE engine being fired at the Engir
Nevada Test Site circa 1968.

The exhaust of the engine in the final days of the program was specific impulse of near 850 seconds, almost three times the kerosene engines of the Saturn V and twice that of the soc LOX/hydrogen engines of the Space Shuttle. The impact of thi example, would have been to reduce the round trip time of a manne the 2.5 years possible with chemical engines, to about 14 months

In addition to the engine performance milestones, the Rover/N demonstrated that the exhaust from a nuclear engine could be s fission products. As the result of increased restrictions on emi the atmosphere, the Nuclear Furnace [7,8] was built in order tc fuel-element materials. The Furnace consisted of a 45 MW react the fuel elements could be replaced with experimental elements t as corrosion. The Nuclear Furnace reactor was followed by a s clean the effluent. The result was a hydrogen jet that contain products.

In 1989, President Bush announced the start of the Space Explora the US. The ultimate goal was to send a manned mission to Mars time, the nuclear rocket was considered as one of the baselines NASA. As part of a joint DOE/NASA team [10,11], Los Alamos wor cost and feasibility of recovering the solid core technology. I requirements of refurbishing the old testing facilities at Nevada

In 1999, the NASA Marshall Space Flight Center funded the Bechtel-Nevada corporation and the Los Alamos National Laboratory to examine t nuclear rocket under today s environmental guidelines using a c Subsurface Active Filtering of Exhaust (SAFE). The concept is highly porous rock strata at the Nevada Test Site to absorb any f during the test of a nuclear rocket. The results of the proje concept could be proven using a RL10-5A engine for a cost of a project further determined that with a $15 M capital layout at t could be tested at full power and full duration for $1.6 M per te

Recently, NASA convened an independent review panel [13] to crit elements of their Advanced Space Transportation Program (ASTP) Space Flight Center was in charge of pursuing advanced concepts This author was a member of the panel. The panel reviewed fo concepts grouped into three categories: 1) Earth to orbit, 2) beyond the solar system. In the final report, the panel recogn term concept available for human missions to the planets was fis two obstacles to obtaining nuclear systems were fuel development The past three years have shown that the testing issue may hav SAFE concept. The only remaining obstacle is a suitable fuel fission product retaining fuel could enable, not only human expl but also cheap access to orbit.

Future Possibilities

Cheap Access to Space

The potential benefits to space exploration are tremendous from the purely technical perspective. If we consider only what might be enabled, we see new opportunities present themselves. Space is not only the final frontier but is also the next marketplace. The orbital space above Earth offers tremendous opportunities for both strategic assets and commercial development. The critical obstacle retarding the use of the space around the Earth is the lack of low cost access to orbit.

Currently, launch to orbit costs NASA over $4 B per year, the
Defense $1.5 B per year, and the commercial market worldwide o
[14]. Thus, the total demand for launch services is almost $9 B.

> The potential for the future [in space] seems limitless
> without affordable and reliable access to space, this potent
> unrealized. — [Daniel S. Goldin, NASA Administrator, testimony befor
> the Senate Subcommittee on Science, Technology, and Space, 1

Reduction in launch costs is expected to result in tremend
Currently, Delta II class rockets launch satellites at around $4
payload [15]. Launch on a Titan IV class rocket will cost aroun
As satellite bandwidth requirements continue to increase, the s
increase in size, mass, and power requirements. These payloads
higher launch-mass capabilities. If the cost of launching a s
reduced to $1000/lb or less, a significant increase in launch d
order to accomplish this, a propulsion system with a signific
impulse must be developed.

Millions of dollars and thousands of people-hours have been spent cost-to-orbit. NASA has investigated several single-stage-to-orb start-up companies have pursued wildly different, innovative co aerospace contractors have tried to reduce costs by streamlining efforts have, so far, failed. They have all suffered from one lowenergy-density of chemical propellants.

If the goal for the cost-per-pound-of-payload, denoted by ε, into orbit is \$500, then the total capital intake by a launch company will depend on the mass of the payload. However, the mass of the entire rocket on the launch pad is also dictated by the payload mass. Thus, the maximum allowable <u>cost per pound of rocket on the pad</u>, denoted by K, can be calculated for a given specific impulse (Isp) and a given ε. The results of a preliminary calculation are shown in Figure 3. The figure shows that in order to develop a economically competitive SSTO one of two approaches must be developed: 1) very cheap fabrication/operation of chemical rockets or 2) a rocket with a significantly greater specific impulse.

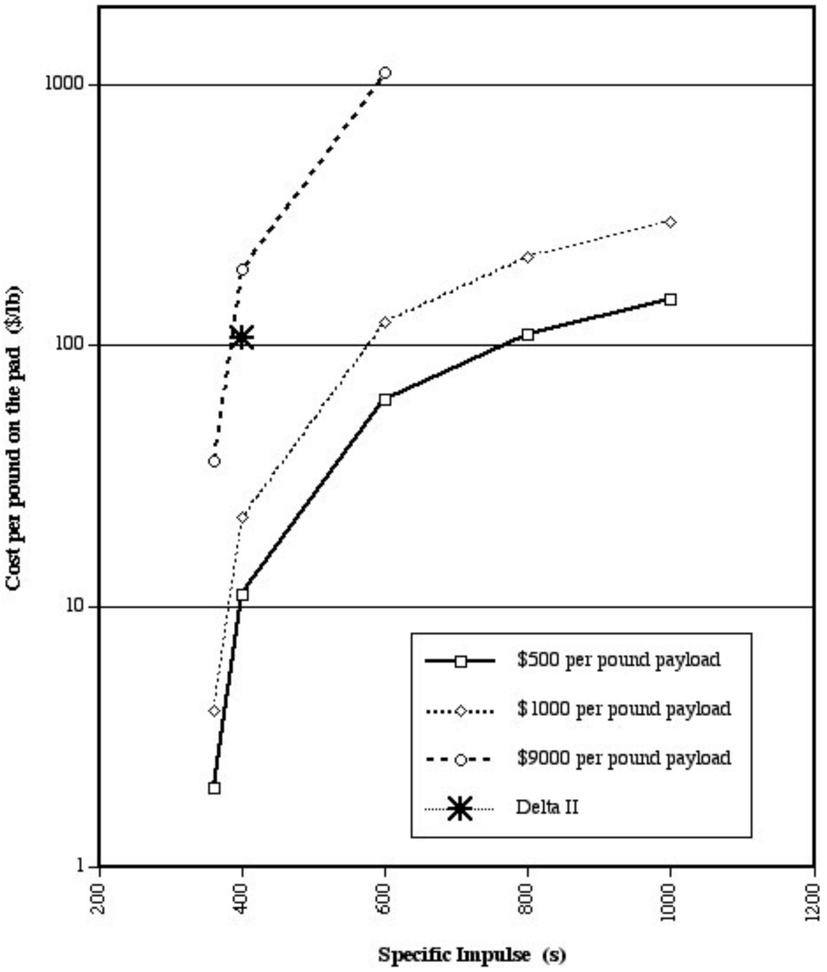

Figure 3. Plot of the maximum allowable cost to put a SSTO ro versus specific impulse. The plots are shown for different valu cost per pound payload The current costs for a Delta II is also the Delta costs to the=500 $/lb-payload shows that a rocket wou Isp=800 s.

Currently, the Delta II costs $55 M and weighs 510,114 lbs on the pad, or $108 $/lb-on-the-pad. Because the technologies used for these vehicles for pumping hydrogen are very similar to the nuclear rocket requirements, these values can be used to set the scale for a nuclear system. The curves in Figure 3 show that for K equal to \$108/lb, the Isp of a nuclear rocket need only be 800 s to deliver a payload to orbit with an ε equal to \$500/lb. But the nuclear rockets tested during the 1960s had a Isp of 850 s. Because of improvements in materials technology in the past few decades, more recent estimates indicate that a nuclear rocket could have an Isp of between 900s and 1000s.

Because the nuclear rocket has an Isp almost twice that of the LOX/LH2 engines, the payload can be put into orbit for the lower cost even though the total cost of the rocket on the pad may be higher. Thus, a nuclear system should be able to put payloads into orbit for around \$500 per pound using technologies currently employed in a Delta class rocket.

Nuclear rockets are a proven technology. The fuel that powered
however, allowed radioactivity to seep into the exhaust stream a
application of the rocket in the atmosphere. Even in today s
rocket can be tested and validated for modest cost. The high pe
system will allow a significant reduction in cost to launch paylo
In order to be acceptable for use, however, the rocket must not
to the exhaust stream. By utilizing advanced fabrication techni
produced that will inhibit the migration of fission products.
products can be interred in the fuel matrix. Since neutrons do
into hydrogen, a clean exhaust of hydrogen gas can be produced.

capability could enable a new, robust, high-performance launc developed.

At first the risks implied from launching a nuclear rocket off would seem to great to even consider. What if it blows up at explodes over a city? The simple fact is that a nuclear syst explosion than the Shuttle. The nuclear system has no combus oxygen tanks rest nearby to hydrogen tanks nor near jets of hot gases. In ac nuclear rocket tested in the 60 s ever had a breach of the pressu pressure of one thousand psi requires a very thick containment vessel. launch abort, only a single entity would return to the surface — debris.

Would the engine be radioactive? Certainly during operation, rac high. The standard standoff distance applied at any rocket laur protect any observers. Is the engine radioactive after operat continue to emit gamma rays for several months. However, these are largely shiel by the pressure vessel and the surrounding material. During required to reach orbit, a nuclear engine will create only 27 gr Most of these are very short lived. Even if the engine did retu abort, workers could handle the unit safely.

The idea of using a fission based system to launch material into orbit be nonsensical. From a technical perspective only, though, it m method to achieve low cost to orbit. The subjective public persp have to alter dramatically to enable such a system to be built.

Sending Humans into the Solar System

Several studies [17,18,19] over the past decade have identified the difficulties of sending manned missions beyond the moon. Most prominent of these are the radiation levels of nearly a REM per week from galactic cosmic rays [20] and the substantial decalcification of bone that occurs in a zero gravity environment. In addition, psychological problems associated with living in confined quarters for long periods of time have been indicated by incidents on board the Russian space station, MIR. The effects of all of these threats can be reduced substantially by reducing the total mission time *to six to ten months*. Alternatively, if the mission scenario allows for return in a previously deployed ship, missions with a *40 day transit each way* could be considered. To accomplish this and maintain a reasonable mass fraction for the Initial Mass in Low Earth Orbit (IMLEO) of the ship, a high thrust system with a specific impulse of near 3000 seconds will be required. The gas-core fission rocket (GCNR) is the most likely candidate to achieve this performance in the near future [21-26].

Because of the high specific impulse afforded by the GCNR, all propulsive, high delta-V missions can be considered. This will provide the crew an active means to adjust to unforeseen events whereas passive concepts like aerobraking may be more susceptible to unknown developments such as a fluctuating Mars atmosphere. Thus, all propulsive missions may reduce the risk of the mission. In addition, the increased performance allows extra shielding against the space radiation environment to be incorporated into the transfer module without a significant increase in the total ship mass in orbit.

MARS Surface Radiation

Roughly 90% of the incident flux of galactic cosmic rays (CR) in space is high-energy protons traveling at roughly 90% the speed of light. The remaining 10% consists of heavier nuclei such as helium, lithium, carbon and on up through iron. The velocity of the heavier constituents, however, closely resembles the spectrum of the protons. In free space, most of the dose experienced by an astronaut will come from the highly charged heavier ions rather than the more plentiful protons. The high specific energy loss associated with heavier nuclei is a dominant feature in shielding humans in space.

On the surface of Mars the dominance of the heavy nuclei is no longer the major component. The Martian atmosphere is thick enough to attenuate most of the heavy nuclei from the CR. This fact has resulted in previous estimates of the potential dose to a human crew being down by a factor of three when compared to free space levels.

This conclusion supported the concept of a long term stay on the surface for early Mars missions.

Although most of the heavy nuclei in the CR are attenuated by the Martian atmosphere, the 95% component of the CR protons and alpha particles are only slightly affected. Thus, the high-energy particles pass through the atmosphere unimpeded and strike the soil of Mars. Typically, each incident particle will produce around 20 to 30 neutrons in the soil. Some of these neutrons will carry forward deeper into the soil and be lost. Many, however, will reflect back out into the atmosphere where they can expose the crew on the surface.

Preliminary calculations estimate that the dose rate on the surface of Mars is about 75% of the rate in free space at that time in the solar cycle. Thus, for a 3 year round trip, the total dose to the crew may exceed their allowable lifetime allotment. This level of irradiation to an unshielded crew may dramatically impact mission planning and may preclude the idea of using conjunction class missions which require the 500 day stays on the surface.

GCNR Technology

Simultaneous with the Rover/NERVA programs in the 1960s, the gas core concept was also experimentally investigated. The erosion and the temperature limitations of the graphite fuel experienced by the solid-core nuclear rocket led several researchers to theorize on the feasibility of having a non-solid, or gaseous core.

A gaseous core would allow far higher temperatures to be achieved and, thus, far higher performance by the rocket. Specific impulses of several thousand seconds were seen as possible. Consequently, experiments in vortex formation, plasma stability, uranium-plasma emissivity, hydrogen opacity, and gas-phase criticality were accomplished in order to determine feasibility. The effort, however, was limited to an empirical experimental program because of the lack of computational capabilities at the time. With plasma dynamics in its infancy, accurate assessment of the chaotic, complex behavior of a fluid-stabilized plasmoid was unreachable.

In the forty years since the Rover program, hundreds of millions of dollars have been spent in plasma research and in developing powerful computational modeling capabilities. The most notable efforts in these areas were the fusion energy programs and the nuclear weapons programs. Both of these large programs relied heavily upon benchmarked computational models to examine stability, operations, and technical feasibility prior to executing expensive experiments. Similarly, the concept of a gas-core nuclear reactor can now be examined computationally before large, expensive and hazardous test facilities must be constructed.

In 1996, the NASA Marshall Space Flight Center funded a small effort to seriously assess the feasibility of the gas core concept using the computational tools and expertise at Los Alamos. As a result of the Los Alamos effort, a new geometric configuration for a gas core rocket has been formulated and is shown in Figure 3. Conceptually, a high speed jet of gas is injected axially into the reaction chamber. As the jet expands across the chamber, some of the gas will exit through the nozzle but some will be recirculated along the outer wall. The recirculation creates a toroidal vortex. In a nuclear system, uranium is injected into the vortex. Driving the uranium to criticality will heat the gas along the axis to extreme temperatures providing a very high specific impulse thrust. This configuration has the advantages of having the highest heat flux be at the centerline of the hydrogen flow stream, of having a thick hydrogen barrier around the walls, and of not suffering the uranium-migration loss mechanism.

There is little doubt that a gas core reactor can be built in a stable configuration and driven critical to produce substantial power and thrust. The questions of final performance with regards to fuel-loss rate, specific impulse, and mass will depend upon the integration of many factors into the final design and must be experimentally investigated. This is the next step.

Sending a human crew to Mars will be risky and substantially more demanding than the Apollo missions. However, the primary risk factors of radiation exposure and physiological degradation can be alleviated by performing fast round-trip missions of months instead of years. The Gas Core Nuclear Rocket offers that potential if it can be successfully developed. Potentially, the rocket could allow a three month transit to Mars, a sixty day stay at the planet, and a four month transit back to Earth. The ship would contain shielding against space radiation, three landers for visiting the Mars surface, and a crew of six - all for an initial mass in Low Earth Orbit that is less than the that of the three-year-long NASA Design Reference Mission, circa 1998. The ability to propulsively brake at the planets and to shield the crew against the radiation makes the GCNR mission one worth pursuing.

From the inception of this project, the complexities and difficulties inherent in the GCNR concept have been recognized. This is a hard problem. It is a grand challenge that, if met, can lead humanity out into the solar system.

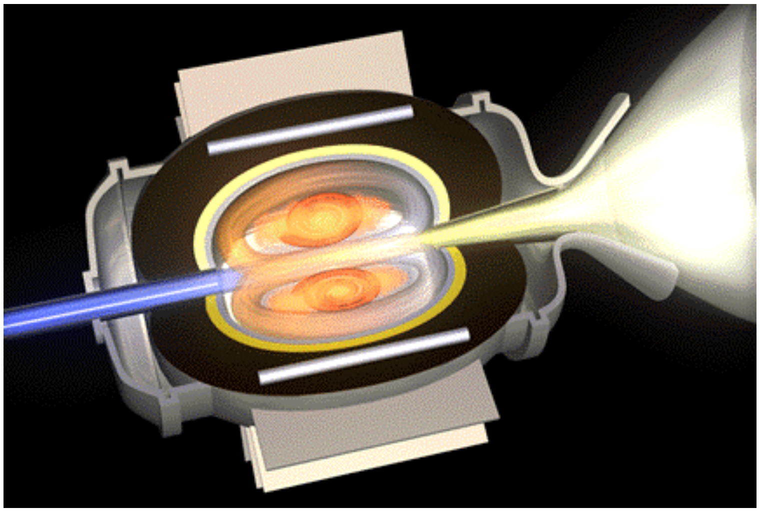

Figure 3. Artist concept showing the flow configuration of a potential gas core nuclear rocket. Conceivably, the engine could have a specific impulse of over 3000 sec.

Summary

If the human race is to expand into the solar system, they will have to face head-on the problem of traveling huge distances in a short time. This requirement translates into a need for high energy density propulsion systems. Fission is the only such system that has been tested and has sufficient performance to enable humanity's expansion.

Two obstacles may impede the development of fission propulsion – sociopolitical and technical. A vocal minority over the past few decades has convinced the general public that fission systems are inherently bad despite the overwhelming evidence that fission systems are the cleanest and most reliable form of power generation. In order to explore space, the public must be educated that the use of fission energy will reduce the risk to human crews, will reduce the overall radiation exposure to the crew, will shorten mission duration, and will dramatically increase the chances of a successful mission.

Fission propulsion is a proven technology. Fission rockets can be tested on the ground safely and relatively cheaply with no exposure to the environment. On the launch pad or prior to operation, a fission rocket will produce 1 million times less radiation than that generated by the Cassini probe launched in 1997. In space, operation of the nuclear rocket will not impact the already high levels of radiation present nor will it be a source of radioactivity to the Earth.

Propulsion is the key to space exploration. Nuclear systems are the best, most practical, highest-performance, near-term option and should be given a fair evaluation without the hindrance of the “N-word” bias. Over the years since the NERVA program, new technologies in materials, in testing, and in reactor concepts have been developed. Combined, these new approaches could enable the safe, clean use of fission propulsion to explore the cosmos. Space exploration is not only the greatest challenge this country can undertake but could possibly be one of the greatest contributors to peaceful coexistence on this planet. But to do exploration, we need high performance propulsion.

A compact, safe, testable fission rocket can provide that capability.

References

1. W. Von Braun, “Mars Project,” 1952.
2. T. F. Widmer, “Applications of Nuclear Rocket Propulsion to a Manned Mars Spacecraft,” Proc. of AIAA Conf., 1963.
3. US Department of Energy WEB site: http://www.ne.doe.gov/isotope/lives.html
4. K. Boyer, “Rover Testing Facilities,” Proc. Of the AIAA Third Annual Mtg., No. 66-1003, 1966.
5. R. W. Schroeder, “NERVA – Entering a New Phase,” Jour. Of Astronautics and Aeronautics, May 1968.

6. S. Howe, “Assessment of the Advantages and Feasibility of a Nuclear Rocket for a Manned Mars Mission”, Manned Mars Mission, W. Mendell editor, NASA M001, 1986.
7. Bohl, R., D. Hanson, and F. Edeskuty, “Planning for Ground Testing of Nuclear Rocket Engines with Today’s Environmental Awareness,” AIAA 90-2517, 26th Joint Propulsion Conference, Orlando, Fl., July 1990.
8. Brengle, R., S. Gunn, and W. Wagner, “Nuclear Thermal Rocket Engine Exhaust Conditioning in Open Cycle and Closed Cycle Systems,” Nuclear Power in Space Conference, Semipalatinsk, Kazakhstan, Sept. 1992.
9. Report of the 90-Day Study on Human Exploration of the Moon and Mars, NASA, Nov. 1989.
10. The NASA/DOE/DOD Nuclear Rocket Propulsion Project: FY1991 Status,” Eds. John S. Clark and Thomas J. Miller, NASA-LeRC, AIAA 91-3413, Sept. 1991.
11. Proceedings of the NASA/DOE/DOD Nuclear Thermal Propulsion Workshop, ed. John S. Clark, NASA CP-10079, Cleveland, OH., Aug. 1991.
12. Steven D. Howe, Bryan Travis and David K. Zerkle , “SAFE Testing of Nuclear Rockets”, AIAA Jour. of Prop. and Power, Vol. 17, no. 3, p. 534, 2001.
13. “Ad Astra per Aspera: Reaching for the Stars”, Report of the Independent Review Panel of the NASA Space Transportation Research Program, Dr. C. Merkle editor, Jan. 1999.
14. Aviation Week and Space Technology Source Book
15. Delta II WEB site: http://www.af.mil/news/factsheets/Delta_II_Medium_Launch_Vehicl.html

16. Titan IV WEB site: http://www.laafb.af.mil/SMC/PA/Fact_Sheets/ttn4_fs.htm

17. "Pioneering the Space Frontier: The Report of the National Commission on Space," Bantam Books, May 1986.

18. Cohen, A., "Report of the 90-Day Study on Human Exploration of the Moon and Mars," NASA, Nov. 1989.

19. Stafford, T.P., "America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative," U.S. Government Printing Office, 1991.

20. Wilson, J. W., et. al., Transport Methods and Interactions for Space Radiations, NASA Reference Publication 1257, NASA, 1991.

21. S. D. Howe, "Reducing the Risk to Mars: the Gas Core Nuclear Rocket", AIAA Aerospace America, August 2000.

22. S. D. Howe, B. DeVolder, L. Thode, and D. Zerkle, "Reducing the Risk to Mars: the Gas Core Nuclear Rocket", Space Technology And Information Forum (STAIF), Albuquerque, NM, 1999

23. Weinstein, H. and R.G. Ragsdale, "A Coaxial Flow Reactor - A Gaseous Nuclear Rocket Concept," ARS Preprint 1518-60, Dec. 1960.

24. Kerrebrock, J.L. and R.V. Meghreblin, "Vortex Containment for the Gaseous Fission Rocket," Sc Jour. Aero/Space., Aug. 1961.

25. Thode, L.E., M.C. Cline, and S.D. Howe, "Vortex Formation and Stability in a Scaled Gas Core Nuclear Rocket Configuration," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 97-2955, July 1997.

26. Howe, S. D., "Nuclear Rocket to Mars", Aerospace America,August, 2000.