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REDUCING THE RISK TO MARS: THE GAS CORE NUCLEAR ROCKET

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Abstract

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. However, because the mission distances and duration will be hundreds of times greater than the lunar missions, a human crew will face much greater obstacles and a higher risk than those experienced during the Apollo program. A single solution to many of these obstacles is to dramatically decrease the mission duration by developing a high performance propulsion system. The gas-core nuclear rocket (GCNR) has the potential to be such a system. We have completed a comparative study of the potential impact that a GCNR could have on a manned Mars mission. The total IMLEO, transit times, and accumulated radiation dose to the crew will be compared with the NASA Design Reference Missions.

INTRODUCTION

Several studies (Paine 1986, Cohen 1989, and Stafford 1991) over the past decade have identified the difficulties of sending manned missions beyond the moon. Most prominent of these are the radiation levels between .01 to .02 Sv per week from galactic cosmic rays 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 eight to ten months. 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 greater than 2000 seconds will be required. The gas-core fission rocket is the most likely candidate to achieve this performance in the near future.

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, extra shielding against the space radiation environment can be incorporated into the transfer module. The benefits of the GCNR become obvious when comparisons are made between the current NASA Design Reference Mission and the NASA 90 day stay option.

GCNR BACKGROUND

In 1955, the Los Alamos Scientific Laboratory began the Rover program to develop a solid core nuclear rocket engine. In 1963, the Nuclear Engine for Rocket Vehicle Applications (NERVA) began with Westinghouse as the prime contractor and Los Alamos as a supporting contributor. Simultaneous with the Rover/NERVA programs in the 1960s, the gas core concept was also investigated (Weinstein 1960 and Kerrebrock 1961). 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 1985, Los Alamos participated with NASA centers in a six month study (Duke 1986) to examine all aspects of a manned Mars mission. During the course of the study, the idea of using the nuclear rocket was reintroduced.

Trade-studies showed that use of nuclear propulsion would reduce the cost of the mission time by at least a factor of two. In addition, the equipment necessary to fabricate the fuel of the nuclear rocket still existed at Los Alamos along with the ability and expertise to test such a system at the Nevada Test Site.

In 1989, President Bush announced the start of the Space Exploration Initiative. The ultimate goal was to send a manned mission to Mars by 2018. This time, the nuclear rocket was considered as one of the baselines for the mission by NASA. As part of a joint DOE/NASA team, Los Alamos worked to show the cost and feasibility of recovering the solid core technology. In parallel, however, the NASA/DOE effort included an assessment of other, higher performance concepts. One of the concepts evaluated was the gas core.

In 1991, the Los Alamos National Laboratory sponsored the Gas Core Nuclear Rocket Workshop (Howe 1991). The goals of the Workshop were to summarize the previous research performed around the country and to identify the outstanding technical issues pertinent to GCNR design and operation. Thirty five representatives from industries, universities, and government agencies attended. Following the workshop, Los Alamos began investigating (Sgro 1991 and Howe 1991) some of the issues in fluid dynamic stability, neutronics, interface mix, computer code applicability, and MHD. The result of these efforts was a recognition that the tools to computationally model the complex interactions of the gas core rocket were now within reach.

GCNR TECHNOLOGY STATUS

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.

Recently, a new, small effort was initiated to seriously assess the feasibility of the gas core concept using the computational tools and expertise at Los Alamos. By applying the knowledge developed over fifty years as part of the nuclear weapons program, the question of developing a rocket that truly opens up the solar system to manned exploration might finally be answered.

From the inception of this project, the complexities and difficulties inherent in the GCNR concept have been recognized. This is a hard problem. Initially, the research has focused on modeling the cylindrically symmetric configuration wherein an annular injection of hydrogen forms a recirculation vortex in the chamber. Once formed, the vortex is replaced with a uranium vortex which will go critical, heat up to around 5 eV, and radiatively couple to the surrounding hydrogen to produce thrust. So far, five different computer codes have been exercised to assess their capability to model vortex formation and stability in a cylindrically symmetric geometry. From the past few months we have ascertained the following for the cylindrical configuration:

1) flow through the base plate can alter the location of the vortex allowing for active control but can actually destroy the vortex if too high a mass flow is injected;

2) the strength of the vortex, the vorticity, depends almost wholly on the inlet velocity for annular injection;

3) for conditions with high levels of vorticity, no shedding or breakup of the vortex was observed;

4) fuel pellet injection and subsequent evaporation appears to be a viable concept for start-up and fuel-loss recovery;

5) “vacuuming out” the fuel back through the base plate appears to be a viable shut-down concept;

6) diffusion of the fuel throughout the propellant volume appears to occur rapidly for the cylindrical configuration, so that fuel retention is low;

As the result of these studies, we have determined that the cylindrical configuration will not scale to full size because the full-scale mass flow will be between 2 to 6 kg/s which, for an annular injection with a radius of .75 to

1.0 meter, would mean the thickness of the annulus would be quite narrow. A narrow injection results in the thickness of the hydrogen propellant between the uranium and the wall will be narrow and relatively transparent to the emitted radiation. The result is that wall heating will be high, propellant heating will be low, and the configuration is not practicable.

During the short time this project has been underway, the team at Los Alamos has made exceptional progress (Thode 1997) in understanding the physics inherent in an open-cycle gas-core rocket, in developing the computational tools to pursue design of a stable configuration, in identifying strengths and deficiencies of those tools, in testing several computer codes against existing data, and in generating an intrinsic “feel” for what operational conditions will be required to make a gas-core rocket feasible. Eventually, we intend to examine critical issues such as shear-flow-turbulence losses of the uranium, mixing caused by displacement of the vortex due to acceleration, the need for sufficient residence time of the propellant in the chamber, fission product removal, and stability of the vortex.

As a result of our efforts so far, the team is confident that a gas core reactor can be built in a stable configuration and driven critical with substantial power generation. 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.

FAST MISSION TO MARS

Historically, missions to Mars have fallen into two categories - conjunction class and opposition class. The conjunction class mission is characterized by low speed transits, usually Hohlman transfer orbits, and a long, roughly 500 day, stay on Mars before returning to Earth. The long stay is required because by the time the ship has arrived at Mars the Earth has proceeded too far around the sun to overtake on a return trip. The opposition class mission usually entails faster transits, higher delta-V breaking requirements at the target planet, and far shorter stay times on Mars, roughly 30 to 90 days. Typical total trip time will be around 430 days. Often, an opposition class mission will necessitate the transfer ship crossing inside the orbit of Venus on return in order to catch up to Earth.

With the GCNR, a third type of mission can be considered -- the point-and-shoot. This is an opposition class mission wherein the ship transits to Mars in a few months, stays from 30 to 60 days, and returns to Earth in a few months. Total trip time is under nine months. This type of mission requires very high delta-V burns at all four staging points - Trans-Mars Injection (TMI), Mars Orbital Insertion(MOI), Trans-Earth Injection(TEI), and Earth Orbital Insertion(EOI). In order to be able to execute such a mission with a reasonable mass fraction of the ship in orbit, the propulsion system must have a specific impulse of around 2000 seconds or higher.

The delta-Vs for a fast transit mission occurring in the Year 2011 are (courtesy of Michelle Monk at NASA/JSC) 6.4, 12.3, 15.3, and 14.7 km/s for the four burns at TMI, MOI, TEI, and EOI respectively. Thus, the total delta-V for all four burns is near 50 Km/s. If the GCNR has a specific impulse of 3000 seconds, then just under 20% of the total ship mass in LEO will be payload and structure-- the rest will be fuel. That is to say, that it will require 4 kg of fuel for every kg of payload to perform the entire mission. Alternatively, for a solid core nuclear rocket to achieve these delta-Vs and perform this mission would require over 100 kg-fuel per kg-payload, a mass fraction in LEO of less than 1%. A chemically propelled system cannot perform the mission.

The fact that the mass fraction is of order 20% also allows another advantage of the GCNR - radiation shielding. Depending upon the year of the mission, the dose to the crew in free space will range between .45 Sv/yr to 1.2 Sv/yr for years of solar maximum and solar minimum respectively. The total dose allowed by the International Committee on Radiation Protection (ICRP) is about 2.0 Sv for a lifetime. This translates roughly into a 15% chance of developing a lethal condition. Annual levels recommended by the ICRP for radiation workers are near .05 Sv/yr. Because of the performance of the GCNR, a layer of shielding material, probably water, could be placed around the transfer module to drastically reduce the radiation levels experienced by the crew.

MISSION COMPARISON

During the past several months, meetings at NASA Johnson Space Center (JSC) have reexamined potential Mars mission scenarios (Hoffman 1997). The baseline assumptions in their Design Reference Mission (DRM) have been: 1) a solid core nuclear rocket for TMI, 2) aerobrake capture at Mars, 3) previously positioned cargo mission to put the return ship, which uses chemical propulsion, into Mars orbit, and 4) aerocapture at Earth. Total mission time is

900 days away from Earth. Total mass in orbit including the three cargo missions is 659 metric tons. The mission profile includes a 6 month transit to Mars, a 536 day stay on the surface, and a 6 month return flight.

In addition, NASA has examined an opposition class mission that would provide a 90 day stay on the surface. This scenario has most of the same mission components as the DRM but has higher delta-Vs, one less cargo mission, and the shorter surface stay.

A comparison of the DRM and the 90-day stay missions with a potential GCNR mission is shown in Table 1. The "full-up" GCNR mission is substantially different from the NASA profiles in that it includes the following: 1) propulsive burns for all four junctures - TMI, MOI, TEI, and EOI, so that development of high performance aerobraking is not required; 2) 40 to 60 day stay on the surface; 3) transits between planets are three to four months, i.e. very high delta-Vs are required; and 4) inclusion of shielding against galactic cosmic rays is optional.

TABLE 1. Mars Architecture Comparison

JSC DRM - 536 Day	**JSC 1B - 90 Day**	**LANL Full Up**
SCNTR - TMI	SCNTR - TMI	GCNR - TMI
6 crew	3 crew	**6** crew
3 cargo missions	2 cargo missions	1 cargo mission
6 month transit to Mars	6 month transit	3 month transit
aerobrake - MOC	aerobrake - MOC	GCNR propulsive- MOC
3 landers - chemical	1 lander - chemical	**3** landers - SCNTR
500 days surface	90 days surface	40-60 days surface
chemical - TEI	chemical - TEI	GCNR - TEI
6 month transit to Earth	6 month transit	4 month transit
aerocapture Earth	aerocapture Earth	GCNR propulsive EOC
NO habitat shielding	**NO** habitat shielding	H_2O shielding - 25 cm (**NO** shielding option)
Round trip time=**900** days	**435** days	**270** days
Total IMLEO of all flights = 659 mT	609 mT	582 mT (460 mT unshielded)
Total radiation dose=**2.04 Sv**	**1.06 Sv**	**0.22 Sv** (0.61 Sv unshielded)

(assumes 0.93 Sv/yr free-space for the year 2011 and 0.8 of free-space, i.e. 0.74 Sv/yr, on the surface of Mars)

The results in Table 1 show that the DRM mission could expose the crew to more than their allowable lifetime limit. The 90-day stay reduces that exposure by half. Alternatively, the full-up GCNR mission reduces the exposure to 0.61 Sv without any shielding mass in the transfer ship. Using a 25 cm water shield around the transfer module results in a total mission dose of 0.22 Sv. As seen in the table, the IMLEO for the missions is 659 mT for the DRM, 609 mT for the 90-day stay, 460 mT for the unshielded GCNR fast mission, and 582 mT for the shielded GCNR mission. Thus, for slightly less mass in orbit, the gas core rocket can perform a 9 month round-trip mission, allow 3 independent landing sites to be explored, carry a crew of 6 astronauts, and protect that crew from the radiation in space.

A more detailed comparison of the GCNR capabilities to the 90-day stay scenario is shown in Table 2. Each comparison in the Table is a variation of the previous. Thus, #1 is the same as the NASA 90-day scenario except that it uses a GCNR for the TMI instead of the solid core nuclear rocket. The #2 column is the same as #1 except that two of the cargo missions are now combined into a single mission. The #3 option assumes the #2 scenario except that the GCNR is now used for the TEI also. The fourth option then substitutes a solid core NTR ascent/descent system for the chemical systems previously assumed. Options 1 through 4 all use aerobraking at MOC and EOC as does the NASA study. Options 5 and 6 are the fast missions from Table 1. Option #5 has no radiation shielding but carries 3 independent NTR landing systems. This may be overly conservative since one such system could perform all three landings. The #6 option is the final, most demanding scenario but offers the lowest radiation dose, fast transits, 3 landings, and a IMLEO lower than the NASA mission.

TABLE 2. Mars Architecture Comparison -- Los Alamos Options

JSC 1B	Los Alamos Options					
90 day stay	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
90 day	90	90 d	90d	90d	**40d**	40d
TMI- SCNTR	**GCNR**	GCNR	GCNR	GCNR	GCNR	GCNR
2 cargo	2 cargo	**1-** cargo **Combine cargo #2 +piloted**	1-Combined	1-Combined	1-cargo	1-cargo
TEI-chemical	chem	chem	**GCNR**	GCNR	GCNR	GCNR
Landers- 1 chem	1 chem	1 chem	1 chem	**1 NTR**	**3 NTR**	3 NTR
Habitat shield- NO	NO	NO	NO	NO	NO	**YES**
IMLEO total- **609 mT**	422	404	200	186	459	**582**
Radiation dose to crew (Sv)- **1.06**	1.06	1.06	1.06	1.06	0.61	0.**22**

The results in Table II show that the use of a GCNR to fulfill the mission profile for the 90-day stay could reduce the IMLEO from 609 metric tons to 186 metric tons (option #4). Even using the GCNR just for the TEI stage allows the ability to combine the cargo missions so that the IMLEO is reduced to 404 mT. Because of these mass savings, any of options 1 to 4 could be improved by adding a water shield around the habitat to protect the crew from radiation without a tremendous penalty in IMLEO.

SUMMARY

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 (between 0.009 to 0.02 Sv per week) 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 40 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 LEO that is less than the IMLEO of the three-year-long NASA Design Reference Mission. The ability to propulsively brake at the planets and to shield the crew against the radiation makes the GCNR mission one worth pursuing. The technology is at hand.

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