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GAS CORE NUCLEAR ROCKET FEASIBILITY PROJECT

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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.

The gas core concept relies on the use of fluid dynamic forces to create and maintain a vortex. The vortex is composed of a fissile material which will achieve criticality and produce high power levels. By radiatively coupling to the surrounding fluids, extremely high temperatures in the propellant and, thus, high specific impulses can be generated. The ship velocities enabled by such performance may allow a 9 month round-trip, manned Mars mission to be considered. Alternatively, we might consider slightly longer missions in ships that are heavily shielded against the intense Galactic Cosmic Ray flux to further reduce the radiation dose to the crew. The current status of the research program at the Los Alamos National Laboratory into the gas core nuclear rocket feasibility[¥] will be discussed.

INTRODUCTION

Several studies[1,2,3] over the past decade have identified the difficulties of sending manned missions beyond the moon. Most prominent of these are the radiation levels between 1 to 2 cSv per week from galactic cosmic rays and the substantial physiological changes that occur 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 of 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 or mechanical breakdowns. Thus, all propulsive missions may reduce the overall 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 (DRM) and the NASA 90 day stay option.

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 at Mars before returning to Earth. The long stay is required because the Earth has proceeded too far around the sun to overtake by the time the ship has arrived at Mars. The opposition class mission usually entails faster transits, higher delta-V breaking requirements at the target planet, and far shorter stay times at Mars,

[¥] This work was performed for the NASA Marshal Space Flight Center under contract #H-28025D.

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 kgs 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 kgs-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 cSv/yr to 120 cSv/yr for years of solar maximum and solar minimum respectively. The total dose allowed by the International Committee on Radiation Protection is about 200 cSv for a lifetime. This lifetime limit translates roughly into a 15% chance of developing a lethal condition. Annual levels for a radiation worker recommended by the ICRP are near 5 cSv/yr, almost a factor of 10 below the levels present in free space. 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.

During the past several months, NASA has reexamined potential Mars mission scenarios. 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 had most of the same mission components as the DRM but had higher delta-Vs, one less cargo mission, and the shorter surface stay.

A comparison of the DRM and the 90-stay missions with the potential GCNR has been made. The "full-up" GCNR mission is substantially different than the NASA profiles in that it includes the following: 1) propulsive burns for all four junctures - TMI, MOI, TEI, and EOI, so that it does not require the development of high performance aerobraking; 2) 40 to 60 day stay on the surface; 3) orbit transfers are three to four months, i.e. very high delta-Vs are acquired; and 4) inclusion of shielding against Galactic Cosmic Rays is optional.

The results of calculations show that the DRM mission could expose the crew to more than their allowable lifetime limit of 200 cSv. The 90-day stay reduces that exposure by half. Alternatively, the full-up GCNR mission reduces the exposure to 61 cSv without having any shielding mass in the transfer ship. Using a 25 cm water shield around the transfer module results in a total mission dose of 22 cSv. 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.

GCNR TECHNOLOGY STATUS

Simultaneous with the Rover/NERVA program in the 1960s, the gas core concept was also investigated[4, 5]. 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 of the time. With plasma dynamics in its infancy, accurate assessment of the chaotic, complex behavior of a fluid-stabilized plasmoid was unreachable.

Because of participation in previous manned Mars mission studies[6], Los Alamos has maintained a familiarity with both solid-core and gas-core nuclear rocket technologies. In 1991, the Los Alamos National laboratory sponsored the Gas Core Nuclear Rocket Workshop[7]. 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[8,9] some of the issues in fluid dynamic stability, neutronics, interface mix, computer code applicability, and MHD effects. 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.

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 able to be answered.

Initial Geometry

Initial calculational efforts focused on modeling the cold-flow experiments performed at the Brooklyn Polytechnic Institute by Professor P. Sforza. The experimental setup, shown in Figure 1, used an annular injection of air around a base plate to form a vortex. This approach appeared attractive in that the vortex could be easily formed, the geometry could be readily modeled, and the experimental setup was still in operation so that specific details of the experiments could be obtained if required. Computational models of these cold-flow experiments have revealed the flow requirements for vortex formation, for separation and shedding, and for establishing oscillations of the vortex location. We have also verified that the position of the vortex can be controlled by a combination of inlet flow and bleed-flow through the baseplate of the chamber. This is an important determination for later designs because its result implies that active control mechanisms can be employed to maintain stability and location of the fuel vortex.

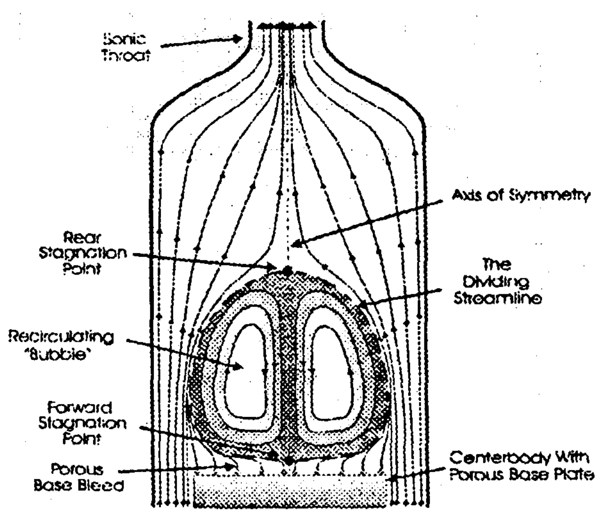

Figure 1. Schematic of the experimental setup of Prof. Sforza at the Brooklyn Polytechnic Institute. (Photo extracted from the Masters Thesis of J. Arzt, Jan. 1996)

Vortex Stability
In two-dimensional cylindrical coordinates with a nozzle, the vortex appears to be stable with respect to disruption and subsequent loss out of the nozzle. With a time-independent injection velocity and inviscid flow, the vortex appears to settle down to a fixed axial position. With a time-independent injection velocity and turbulent flow, the axial and radial position of the vortex continue to move around. The motion does not appear periodic. Nevertheless, the size of the movement is less than 10% of the size of the vortex.

After vortex stability, the next most important feature of the recirculation region is the vortex size. If a vortex is to provide useful confinement for the uranium plasma, the vortex size must be set by the geometry. If the vortex is smaller, then the uranium criticality will be degraded.

A series of coarse and fine zone simulations were performed to investigate the vortex size as a function of injection velocity. In each simulation, the nozzle position and subsonic convergence angle are the same. However, the nozzle throat is changed to match the modified inlet mass flow. Except for nozzle throat modifications, these simulations are for the Sforza geometry.

Between an inlet injection velocity of 1 m/s and 3 m/s, we observe no vortex formation with a coarse mesh. A fine mesh is required. As in the coarse mesh simulations, once formed, the vortex evolves. It moves downstream and continues to increase in size. The fine mesh results are indicated by X symbols in Figure 2.

To date, in full-scale GCNR simulations we have been unable to form a vortex at low inlet injection velocity, despite the fact that the local effective Reynolds number exceeds 500. On the other hand, in full-scale GCNR simulations at high inlet injection velocity, a vortex forms and evolves to a size set by the geometry. In other words, the scaled and full-scale simulations behave in similar fashion at high inlet injection velocity. At this point, we believe the problem with full-scale simulations at low inlet injection velocity is a mesh limitation, which ultimately translates into a simulation time problem. Unfortunately, in the near term, with the required mesh, our simulation time estimate of a full-scale configuration makes a time-dependent model very difficult to implement without a realistic knowledge of the initial flow. We believe this initial flow can be obtained from the steady-state option in the FLUENT code, to be used as an initial condition for the more realistic time-dependent codes.

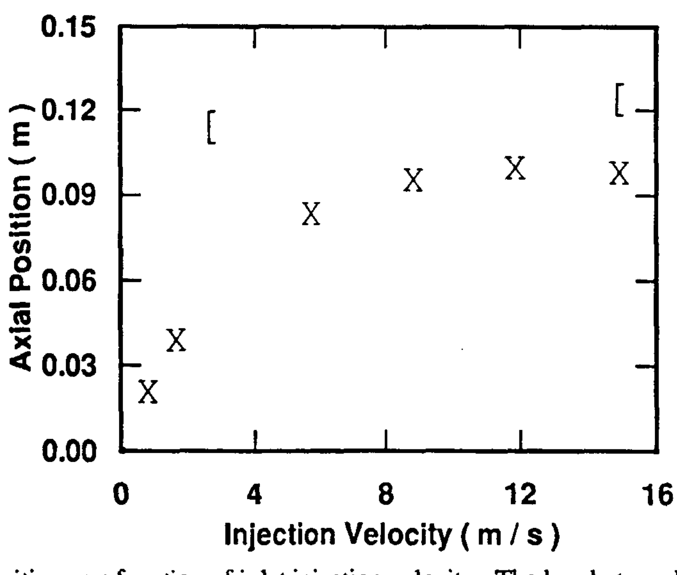

Figure 2. Axial vortex position as a function of inlet injection velocity. The brackets and the Xs represent course and fine zoning respectively.

Impact of the nozzle
The results of a series of simulations from the VNAP2 code are summarized in Figure 3. In the figure, the nozzle position is given in terms of the base plate radius. As expected, once the nozzle position exceeds about three times the base-plate radius, the vortex position is weakly dependent upon the nozzle position. As the nozzle position is decreased, the vortex axial and radial position both decrease. As the nozzle position approaches the base-plate radius,

the rate of change in the axial position of the vortex begins to slow because the vortex is being pushed against the base plate. In contrast, the radial vortex position continues to decrease.

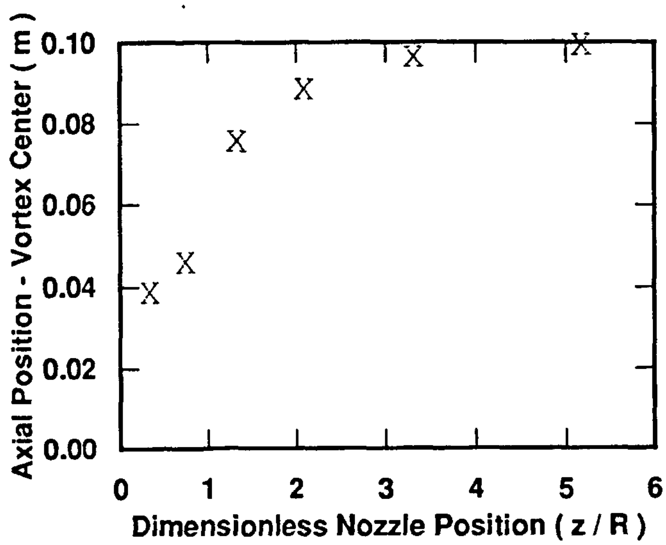

Figure 3. The axial position of the center of the vortex as a function of nozzle position relative to the base plate radius.

From these simulations, the engine nozzle must be included in a gas-core nuclear rocket model to correctly understand vortex formation and vortex stability. In making this statement, we assume the engine will be as compact as possible to reduce the mass of the rocket. In addition, a self-consistent treatment of the nozzle will impact the uranium loss rate out the nozzle.

In two-dimensional cylindrical coordinates with a nozzle, the vortex appears to be stable with respect to disruption and subsequent loss out of the nozzle. With a time-independent injection velocity and inviscid flow, the vortex appears to settle down to a fixed axial position. With a time-independent injection velocity and turbulent flow, the axial and radial position of the vortex continue to move around. The motion does not appear periodic. Nevertheless, the size of the movement is less than 10% of the size of the vortex.

Lessons learned and a new configuration

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 would be 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. Thus, 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.

Consequently, we now propose to begin investigation of a new, innovative configuration that will allow sub-scale experiments to be performed but will scale to full size for the final application. In addition, this configuration should nullify any penalty due to ship acceleration, should increase residence time of the propellant so that it achieves full temperature, and should allow for better neutronic coupling between the reflector/moderator and the uranium plasma. A schematic of the configuration is shown in Figure 4. The basis of the design is that a narrow diameter, high speed jet of hydrogen will be injected along the axis toward the nozzle. This jet will pass through the center of the toroidal uranium plasma where the radiation coupling will be maximized. Some of the jet will pass through the nozzle and some will circulate to form the vortex. This will allow a thicker layer of propellant to circulate around the uranium which should decrease thermal loads on the wall. The vortex will also have a perpendicular velocity component in addition to the recirculation. This will inject the uranium with an azimuthal velocity. This slight centripetal force added to the uranium should reduce the loss rate due to mixing in the high speed, shear-flow region.

Although, this configuration is more realistic, it is more complex. We believe that it will have, intrinsically, properties that benefit the operation and performance of the engine. For example, under acceleration, the vortex will not be driven toward the nozzle directly which would increase the uranium loss rate. Also, the hydrogen passing down the axis will experience the maximum heating rate from the uranium. Although much more realistic, this new configuration will require a three-dimensional capability with radiation transport, neutron transport, and plasma transport. This class of calculation is only possible on the new high-performance supercomputers being developed in the DOE Advanced Strategic Computing Initiative.

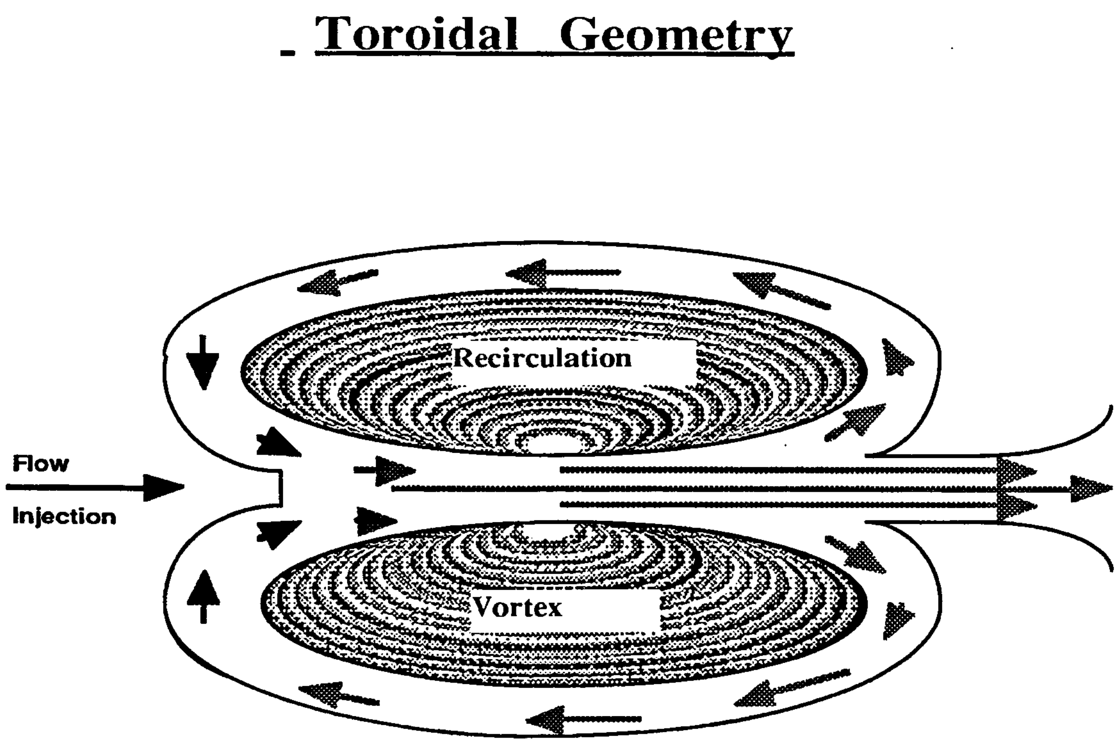

Figure 4. Possible toroidal configuration for the GCNR

During the short time this project has been underway, the team at Los Alamos has made exceptional progress[10] 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 the 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.

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 0.9 to 2.3 cSv 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 the 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 NASA Design Reference Mission which is a 3 year round trip mission.

In conclusion, we have completed the assessment of the open-cycle GCNR in cylindrical geometry. We have established the importance of including accurate nozzle contours in the calculations -- a fact that many previous studies neglected. The sensitivity of the vortex in this geometry has also been examined. To be effective as a GCNR, the reaction chamber must be sufficiently large to allow the uranium to go critical. The cylindrical geometry cannot scale to sufficient size and maintain reasonable mass injection/velocity/thickness characteristics. Thus, we conclude that the cylindrical geometry is not a viable configuration.

Because of the results of these efforts, we now believe that a better design for the GCNR is the counter flow toroidal configuration. This will intrinsically solve many of the problems plaguing earlier gas core designs such as loss due to acceleration, short residence time of the hydrogen and the uranium, and reduced thickness of the hydrogen boundary layer. We intend to examine this design for performance, stability, and sensitivity.

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.

Acknowledgments

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References

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

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

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

4. Weinstein, H. and R.G. Ragsdale, "A coaxial Flow Reactor - A gaseous Nuclear Rocket Concept," ARS Preprint 1518-60, Dec. 1960.

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

6. "Manned Mars Mission," NASA M001, 1986.

7. Howe, S.D., "Proceedings of the Gas Core Nuclear Rocket Workshop," LA-UR-91-1250, April 1991.

8. Sgro, A. G., R.L. Bowers, and R.A. Gerwin, "Two-Dimensional Modeling of a Gas Core Nuclear Rocket," LDRD Project Final Report, 1991.

9. Howe, S.D. and R. L. Bowers, "Preliminary Computational Investigation of an Open Cycle Gas Core Rocket," Conference on Advanced SEI Technologies, AIAA 91-3516, Sept. 1991.

10. 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.