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OVERVIEW AND FUTURE OF OPEN CYCLE GAS-CORE NUCLEAR ROCKET

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Human exploration of entire solar system can be enabled if the gas core nuclear rocket concept is made feasible. The Gas-Core Nuclear Rocket has the potential to greatly reduce the trip time for a given mission as compared to chemical or electric propulsion systems. Operating at high temperature (10^4 – 10^5 K), the Gas-Core Nuclear Rocket achieve specific impulse (approaching 5000 s) and high thrust, essentially eclipsing conventional solid core nuclear thermal rockets. Challenges to the realization of this technology include 1) stably confining fissioning plasma, 2) preventing plasma erosion due to mixing and subsequent entrainment with hydrogen fuel, 3) optimizing heat transfer from the uranium plasma to the hydrogen fuel, and 4) protecting the nozzle from the high-temperature exhaust. In this review, past gas core nuclear technology development is surveyed along with a discussion of the current status of the technology.

I. INTRODUCTION

Gas-Core Nuclear Rockets has the potential to literally open up the solar system to human exploration by reducing the trip time considerably. One of the major problems facing human space exploration to Mars and beyond are the physiological effects of long term exposure to the space environment. These hazards include increased radiation dose, particularly by heavy ions, psychological impacts associated with isolation/confinement, and the deleterious effects of microgravity. Long-term human exposure to weightless conditions can cause mineral loss in bones, vision degradation, loss of bone mass, immune system suppression and cardiovascular deconditioning.[1] Space radiation exposure increases the risk of cancer for astronauts. Current and near-term envisioned propulsion systems such as chemical or advanced electric propulsion systems can ferry humans to mars over trip times of the order of a year. Such trips rely on idealized launched windows. Quick outbound trips translate into long returns. Studies show that the Gas-Core Nuclear Rocket enables roundtrip mission times of only 80-days to Mars.[2] The faster trip times greatly reduces physiological degradation associated with long-duration spaceflight. If realized, the gas core rocket can become the basis architecture for human exploration of the solar system, reaching essentially all planets with round trip times of less than a decade.

Gas-Core Nuclear Rockets are attractive because they feature high-impulse ranging from 2,500 to 7,000 seconds[3], and high-thrust ranging from 20,000 to 400,000 newtons.[2] The gas-core nuclear rocket fuel is in gaseous form allowing for arbitrarily high core temperatures (>10 times solid core operating temperature). Because specific impulse scales with the square root of the gas temperature, significant increase in performance on conventional rockets is possible. Figure 1 illustrates the operation of an open cycle Gas-Core Nuclear Reactor engine, which uses uranium or plutonium as the fissioning fuel. The focus of this review is the open cycle gaseous core reactor. In Gas-Core Nuclear Rocket, the fissioning fuel reaches temperatures more than 55,000 K, which implies that the core is in the plasma-like state. This plasma-like core heats a light gas such as hydrogen and then converts the high enthalpy hydrogen flow via a converging-diverging nozzle to create a high thrust, high-velocity flow to generate thrust. At these high temperatures, hydrogen gas dissociates leading to even further improvements in specific impulse owing to the inverse square root of mass dependence.

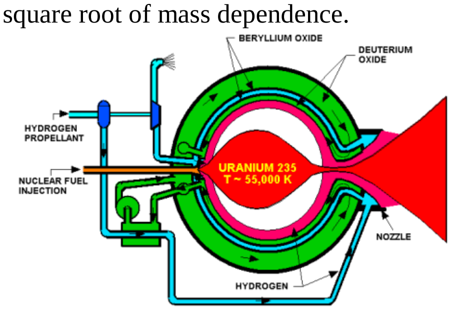


Fig. 1. An open cycle gas core nuclear rocket engine.[5]

Past open cycle concepts have featured hydrodynamic confinement of the fissioning core. The core itself is open to the nozzle and thus nuclear fuel can be entrained and lost with the passing and subsequently exiting hydrogen flow. Hydrogen is heated radiatively by plasma emission in this concept. In the closed cycle configurations, the fissioning plasma is physically isolated from the hydrogen field thereby eliminating nuclear core fuel losses. The nuclear light bulb is an example of a closed cycle system where the hydrogen gas is heated via UV light which passes through a quartz jacket. To achieve reasonable heating, the hydrogen flow field is seeded with micron-sized particles which absorb the UV and act as a heat exchange medium.[4]

In solid core nuclear rockets, the maximum core temperature and thus maximum specific impulse attainable is limited by the melting point of the fuel.[6] The fuel is isolated from the material surface in case of a gas-core nuclear rocket, thus allowing the fuel to operate at super high temperatures.[7] Figure 2 shows the initial mass in Earth's orbit versus mission time for a solid core, open cycle gas core, and regenerative gas core engines.[2] As can be seen here, clearly gas core technologies are superior to solid core requiring less propellant to carry out fast trips to Mars.

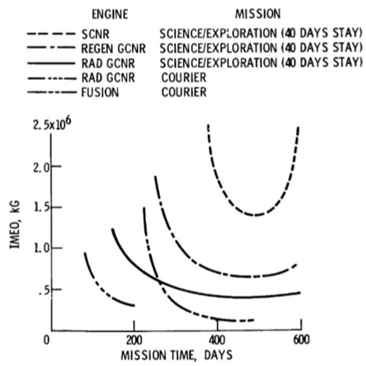


Fig. 2. Mars round-trip mission duration for various nuclear rocket engines versus IMEO.

II. CHALLENGES OF AN OPEN CYCLE GAS-CORE NUCLEAR ROCKET ENGINE

While the realization of gas core nuclear reactor performance would represent a significant advance in rocket technology, a number of technical challenges stand in the way of its development and eventual implementation. As mentioned previously, the chief challenges include 1) stable confinement of the fissioning plasma, 2) minimization of uranium plasma erosion due to mixing and subsequent entrainment with hydrogen fuel, 3) optimization of the heat transfer from fissioning uranium plasma to the hydrogen fuel, and 4) nozzle survival. Loss of fissioning fuel can occur via hydrodynamic instabilities that can arise from the motion of hydrogen fuel around the uranium plasma core and Raleigh Taylor type fluid instabilities where a heavy fissioning plasma is supported by light flowing hydrogen gas. Hydrogen fuel of density ρ_2 and velocity v_2 flowing around stationary Uranium plasma of density ρ_1 under the influence of acceleration 'a' can lead to Kelvin – Helmholtz instability as well (e.g. velocity shear which can lead to mixing and ultimately disruption of confinement), which is expressed as below[8]

$$v_2^2 > \frac{a(\rho_1^2 - \rho_2^2)}{k\rho_1\rho_2} \approx \frac{a\rho_1}{k\rho_2} \qquad (1)$$

Here it is assumed that uranium density is much larger than the hydrogen density. 'k' is the wave number of the oscillation. Confinement must minimize fuel loss while isolating the fuel from the walls.[9] Stability and confinement of uranium plasma, as well as heat transfer to the fuel, are still not well understood. The design goal of a gas core engine is to maximize heat transfer to the fuel while running the core as high as practically achievable and keeping this core in stable confinement with minimum fuel erosion.

III. PAST RESEARCH ON GAS-CORE NUCLEAR ROCKET

Significant investigation into the gaseous core rocket concept extended from the 1960s into the early 1990s.[6-15] This research can be divided into five categories: rocket operations, reactor physics, fluid mechanics, heat transfer, and gas-core confinement studies. Each of these categories is reviewed further in the following sections.

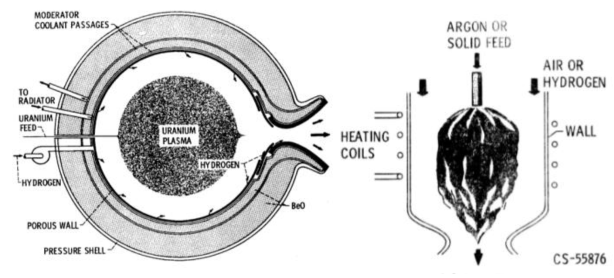
III.A. Rocket Operations

The most common open core design is shown in figure 1. Here the fissioning uranium plasma acts as the fuel element. The hydrogen propellant that flows around the uranium plasma is heated by UV absorption. The heating is most efficient if plasma is sufficiently hot where it emits significant UV light. In particular, hydrogen absorbs well in the Lyman series of wavelengths.

The engine startup scenario for a gas core nuclear reactor is not straightforward. The key is to establish confinement of the core hydrodynamically and then bring that core to criticality. One of the proposed ideas for startup featured the use of antiproton annihilation to generate the required number of neutrons to initiate the fission reaction.[10] In one study it was found that a source of about 10^{22} neutrons is needed for the startup.[6] Another proposed concept involved the injection of a thin rod of uranium metal through a shielded pipe that penetrates the moderator into the cavity region where hydrogen has been pumped to a pressure of 5.07×10^7 to 20.34×10^7 newtons per square meter.[2] The uranium fuel then achieves criticality and power would be allowed to increase to a level such that the uranium rod is eventually vaporized thus giving rise to the gas core. Figure 3 (a) depicts this concept with the uranium fuel feed approach.

III.B. Reactor Physics

Reactor kinetics studies have been conducted to study the critical mass requirement of cavity reactors. Critical mass design considerations include fuel density, fuel density variation with temperature, reflector temperature and neutron utilization as well as geometrical aspects such as core and reflector shape. Experiments were conducted for both cylindrical and spherical geometries, and for both solid and gaseous (uranium hexafluoride) nuclear fuel at Idaho-Nuclear Corporation to study the uranium fuel mass and configuration requirements.[2] The focus of the research was to calculate fuel mass, propellant pressure, cavity diameter, and reflector-moderator thickness for a gas core engine. A summary of results from this study can be found in reference 2. The reactivity and the criticality calculations were made using the neutron transport code TDSN with spherical geometry.[11] Table 1 summarizes the notional configuration of the gas-core nuclear rocket derived from the study in references 11 and 12.



(a) (b)

Fig. 3. (a) Porous gas-core nuclear rocket with Uranium feed system; (b) Experimental Schematic using inductive heating.[2]

TABLE I. Sample Engine Specification.[11, 12]

Engine Parameters	Specifications
Impulse (s)	5000
Thrust (N)	110,000
Propellant	LH2 Seeded with Tungsten
Fuel	U-233 enriched to 98%
Reactor Power (MW)	3,750 Thermal
Total Engine Mass (kg)	91,000
Cavity Diameter (m)	2.4
Moderator Thickness (m)	0.76

Americium has also been investigated as a potential fuel. ^{242m}Am has a large thermal fission cross section. This leads to a significantly smaller reactor (comparable fuel density as that of ^{235}U and a radial size reduction of about 70 percent) that can produce the same performance as that of ^{235}U gas-core nuclear reactor.[6] However, it was found thermal hydraulics and neutronics computational study favors ^{233}U as the best fuel due to its epithermal fission cross sections and hydrogen as the best propellant due to low molecular weight.[14]

III.C. Fluid Mechanics

Fluid mechanics studies have also been carried out to understand the factors that govern the fission fuel loss rate as a function of hydrogen propellant flow rate/flow velocity as well as injection geometry. Isothermal flow experiments were conducted using an air/air (fuel/propellant) cylindrical system. One such study showed that the fuel volume consists of only 20 or 30 percent of the cavity volume. Under these conditions, less than one percent by mass of uranium in the exhausted hydrogen gas from the engine.[2] These experiments were extended to spherical, porous-wall geometry with inductive heating to study the flow characteristics of gas-core nuclear rocket engines. Inductive heating was used to simulate the heating that comes from fission. Figure 3 (b) shows the experiment schematic of the test using inductive heating.

III.D. Heat Transfer

Heat from the uranium plasma needs to be absorbed completely by hydrogen propellant and then be stored as internal energy until the heat is converted into thrust by the nozzle. The heating of the propellant occurs mostly by radiative heat transfer. Energy not absorbed by the fuel thermally loads the cavity wall and nozzle. To reduce this heat loading, studies have been carried out to optimize the energy transfer to the hydrogen gas. Experiments show that adding tungsten particles (micrometer size) to hydrogen gas will produce a mixture absorption cross section ranging from 2000 to 100,000 square centimeters per gram. The study also demonstrated that the absorption increases with higher pressure too.[2] At very high temperature (15,000K), hydrogen itself becomes quite absorptive.[2] In this respect, the seeded hydrogen is only necessary at low operating core temperatures.

III.E. Gas-Core Confinement

Confining the nuclear gas core has proven to be a challenging problem. The conventional approach to gas core confinement features hydrodynamic containment. This approach was experimentally tested to assess feasibility. The geometry of the approach is shown in figure 5. Here injected gas flows past at porous diffuser through which propellant is also injected. This creates a vortex in which the uranium plasma can be injected and confined. The flow through the diffuser keeps the uranium core off the surface of the diffuser – essentially the flow obstruction that generates the vortex. This study showed that a secondary injection of gas (first the uranium fuel is injected, then followed by hydrogen propellant) at the base end of the gas-core would reduce the fuel loss. The recirculation region displaces itself as a bubble away from the core. Figure 5 below shows a schematic of a flow simulation system that was used in the study.[13]

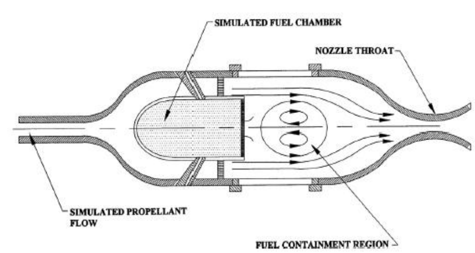


Fig. 5. Base bleed stabilized gas-core nuclear rocket.

Since the gas-core operates at very high temperatures, the gas-core is in a partially ionized plasma state. This ionized state enables the use of magnetic fuel containment. Previous studies have focused on confining the plasma using "mirror geometry" in which the magnetic fields at the ends are stronger than the magnetic field at the center where the uranium plasma core is situated.[8] However, it was found that magnetic mirror confinement at practical field strengths is not feasible owing to collisions which would scatter nuclear fuel into the loss cone. The last significant computational effort addressing the gas-core nuclear rocket problem was carried out by Posten. His study showed that increasing reactor power or rocket acceleration could severely degrade fuel containment. He recommended acceleration-assisted containment for fuel containment.[14] Reference 15 shows the importance of including accurate nozzle contours in computational studies for vortex formation and stability of the system. An alternative confinement geometry considered is a counterflow toroidal configuration.[15]

IV. CURRENT & FUTURE RESEARCH ON GAS-CORE NUCLEAR ROCKET

At the University of Michigan, gas core stability and heat transfer are currently under investigation using a combination of commercial codes such as Fluent for flow and fissioning mass stability (vortex stabilized) and MCNP for neutronics as well as an analytical formulation for the study of heat transfer to the gas. The models designed will be self consistently coupled as the neutronics impacts uranium fuel temperature and heat transfer. Instabilities can not only impact heat transfer but also the neutronics. The goal of research at the University of Michigan is to study stability, heat transfer and fuel loss rates in details as well as to explore new designs based on these studies. Findings from the computational model will be validated using a simple experimental model. The planned computational and experimental study at the University of Michigan are given in the below sections.

IV.A. Computational Study

The computational study will be carried out on the system shown in figure 5 as well as on a counterflow toroidal geometry suggested by reference 15. The focus is to formulate a model for vortex stabilization flow with relevant nuclear densities, temperatures, and cold hydrogen fuel flows. The plasma core is stabilized using a gas vortex formed at the base of the core. Here we maximize the uranium plasma contact surface with the hydrogen fuel. With this model, the density and temperature gradient across the boundary layer can be predicted. It may be possible to drive current through the plasma to drive the formation of a magnetic field to reduce radial losses. Improving confinement of the core using a magnetic field will also be investigated using this computational model.

Neutronics and criticality of the confined uranium plasma will be determined using MCNP. The criticality of the fissioning plasma depends not only on the reflector but also on the local density and shape of the fuel mass. The thermal data will be used to assess the reactivity temperature coefficient to determine the sensitivity and understand the best way to throttle and control the reactor. By varying the nature of the flow field, the shape of the plasma changes as does the power production profile. The design of the reflector also depends on the stability and shape of the fuel. This will also be investigated. Through the simulation of erosion, inferred from the Fluent model, the uranium replacement rate will be assessed. The goal here is to minimize this loss.

A simple heat transfer model will be used to assess heat radiative heat transfer as well as conduction and convective heating of the hydrogen gas. The disassociation state of the exhausted hydrogen and associated I_{sp} will also be calculated. Heat transfer via particle seeding of the flow field will also be investigated. Thermal loading to the reflector will also be studied. This allows for an assessment of cooling requirements for the reflector. Ultimately the goal here is to determine the parameter space that optimizes the design of a realistic gas core reactor. Instability growth rate will also be mapped using fluid analysis. This will give a better understanding of the parameter space of stability. The results obtained from the computational study will be validated using experimental study described below.

IV.B. Experimental Study

Complementing the modeling effort will be an experimental study designed to not only validate the computational model but also provide a real insight into the actual operation of a non-nuclear gas-core-like reactor system. Figure 6 below shows the experimental setup that is planned to be used for this study. A low vapor pressure ionic salt, which is sonically trapped, will serve as the surrogate for the heavy uranium fuel. The salt, which is liquid, will be heated over a broad range using a pulsed YAG laser.

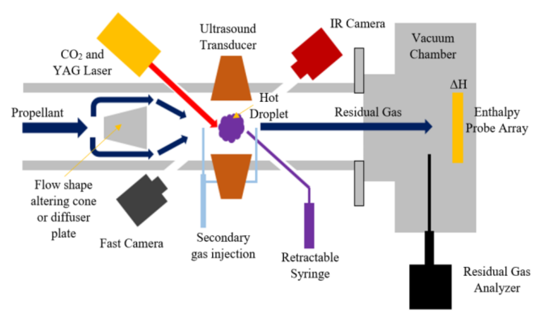


Fig. 6. Proposed experimental setup to study gas core dynamics and energy transfer.

The ionic salt will be levitated both in static and gas flow conditions. Thermal imaging will be used to quantify laser heating of the ionic salt. The fast camera and PIV laser will help to study the instabilities at the interface and will provide an understanding of the overall stability of the droplet. The differentially pumped RGA will help to assess erosion of salt in presence of helium gas (helium is used instead of hydrogen for safety reasons) flow.

Once the apparatus has been fabricated, we will study 1) surface instabilities, 2) fuel erosion, 3) heat transfer to the fluid via enthalpy probe, and 4) characterize the thermal profile of the droplet. Using the differentially pumped vacuum system, we will study mass loss from the droplet with a residual gas analyzer. The parameter space for this droplet will be mapped and used to serve as a test case database for model validation. The findings will be used to not only to refine the model but also physically better understand the stability and heat transfer dynamics of geometries akin to that prevailing in gas core reactors. Addition of a magnetic field to this model will also help to understand the magnetic confinement of uranium plasma. The sensitivity of the position of the confining vortex to nozzle geometry will also be studied. The findings will be used to refine confinement and heat transfer in gas core designs, paving the way for the someday realization of a gas core rocket.

V. CONCLUSIONS

Gas-Core Nuclear Rocket is an attractive propulsion system owing to its high specific impulse and high thrust capability. This engine enables fast trip times and literally opens the solar system for human exploration. Uranium plasma instability, uranium erosion and heat transfer from the uranium plasma to the hydrogen fuel are major engineering challenges. Previous work has yielded a great deal of insight into these technical challenges. The goal of the current research effort is to improve the understanding of gas-core nuclear rocket by a combination of experiments and computational modeling. Through a better understanding of Gas-Core Nuclear Rocket, credible designs can be designed, which can someday lead to implementation, serving perhaps as the basis of human interplanetary propulsion architecture.

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