IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 14, Issue 7, July 2024, ||Series -1|| PP 38-45

The Feasibility Of Nuclear Gas Core Rockets In Interplanetary Travel

Aditya Jadoun
Bhasker Singh
Rakshit Nair

Abstract
It is inevitable that the human race would eventually seek to explore other planets and set foot on them. Chemical Engines are our primary method of traveling across the solar system, especially crewed travel or travel involving very high payloads. However, these engines simply do not possess the efficiency (Specific Impulse) required for fast and frequent Interplanetary travel. Therefore, we suggest the utilization of a nuclear engine, A nuclear gas core open cycle engine. These engines would have the thrust of a chemical engine combined with the efficiency of nuclear fission resulting in an engine with almost 4-8x the efficiency of a conventional chemical engine. We also hope to explore a possible application of this engine.

I. Introduction:

It is no surprise to anyone that the human race has always yearned to explore what they had not explored yet. It is only natural that once we had sailed every ocean and charted every island, this curiosity would expand to space and the planets in it. All human missions in space have used either chemical engines or ion engines apart from a few experimental ones, but chemical engines are the most prolific, and manned spacecraft have only ever used them.

However, this reliance on chemical engines has major downsides. For one chemical engines are extremely inefficient in the grand scheme of things, the energy released from the breaking of chemical bonds is minuscule compared to the breaking of the nuclear force which releases energy in fission, or the 100% energy released in Matter-Antimatter annihilation. As such chemical engines require massive stores of fuel in order to achieve a high Delta V (How much a spacecraft may change its velocity) and as such have longer travel times as well.

In this paper, we specifically explore the advantages of fission-based nuclear thermal rockets, specifically the open cycle gas core engine as an alternative propulsion method. The choice of Nuclear fission was because of two major things, the vast amount of research done into nuclear fission and its technological readiness when compared to fusion. After all, Nuclear Reactors provide 10% of the world's electricity today.

The Gas Core nuclear engine is perhaps the most advanced fission rocket engine designed to date, yet still in the realm of feasibility. There are many problems with this design which we hope to provide solutions to later on in the paper. Along with this we shall look at various advantages the Gas-Core design poses.

Moreover, Nuclear Engines have the capability to be utilized in a sort of interplanetary "ferry" system, due to their high specific impulse and slow usage of propellant.

II. The Basic Principle Of Rocket Engines:

Rocket engines work on the basis of Newton's Third Law of Motion, Every action has an equal and opposite reaction. The most basic form of a rocket "engine" is a pressure-fed engine, A tank of propellant with high pressure, a valve, and a place for the propellant to exit (The nozzle). This results in the propellant going in one direction, exerting a force equal to the mass * acceleration of the propellant(Force = Change of momentum with change in time). For rocket engines, where the propellant is a fluid, keeping an accurate track of the mass is very difficult so rather we look at the mass flow rate, (Mass per unit time) (Ref 1)

$$\frac{d}{dt}m = \dot{m} = r * V * A$$

Where r = Density, V = Velocity, A = Area, ṁ = Mass flow rate

$$F = \frac{Change\ in\ Momentum}{Change\ in\ Time}$$

As the mass flow rate is dependant on time and Exhaust Velocity is constant, We can substitute it into Newtons Second law

Momentum = Mass * Velocity
Force = Mass * Velocity with respect to time,
Therefore, Force in a rocket would be:

$$F = \dot{m} * Ve$$

Where Force = Thrust, ṁ = Mass flow rate, Ve = Velocity at exhaust (Exhaust Velocity)

This is the principle equation for rocket thrust.

To calculate the efficiency of the rocket engine, we look at its specific impulse. As we all know, the formula for impulse is force * Change in Time (Ref 1)

$$I = F * \Delta t$$

We know force in a rocket engine = mass flow rate * exhaust velocity, thus we can write impulse as

$$I = \int \dot{m} Ve \ dt$$

As ṁ is the rate of flow of mass, (it is with respect to time) we can integrate this

$$I = mVe$$

Where m = total mass of propellant, Ve = Exhaust Velocity

Now to get the specific impulse, we simply divide the impulse by the weight of the propellants, m gets canceled and we are left with

$$Isp = \frac{Ve}{g}$$

Substitute formula for Force(ṁ * Ve) to get

$$Isp = \frac{F}{\dot{m} * g}$$

Where Isp = Specific Impulse, F = Force (Thrust), ṁ = Mass flow rate, g = Acceleration due to gravity (9.8 m/s^2 for earth)

Delta V, Or the amount a spacecraft may change its velocity assuming no drag is expressed in this equation

$$\Delta V = Ve * ln(\frac{Mw}{Md})$$

Where Ve = Exhaust Velocity, Mw = Wet mass, Md = Dry mass

III. The Principles Of A Nuclear Thermal Engine

The main difference between a Nuclear Thermal Engine, and a normal chemical engine is the source of power for the energy for the propellant.

In chemical engines, the energy to heat the propellant and accelerate it to high velocities is released by the breaking of chemical bonds. Two main types of chemical engines exist, Monopropellant and Bipropellant. Monopropellant engines typically pass their singular propellant through a catalyst so that it decomposes, releasing energy that heats the propellant and accelerates it. A common monopropellant used is Hydrazine (N2H4), it passed through a catalyst (Alumina granules coated with iridium). It decomposes in contact with the catalyst, releasing a lot of energy and heating the produced gases to high temperatures. (>573 Kelvin) (Ref 2)

Bipropellant engines work much the same way but can take advantage of reactions with more than one reactant. As there is no oxygen in space, rockets need to carry their oxidizer typically in the form of Liquid Oxygen for higher density. An example of a widely used bipropellant reaction would be

$2H_2 + O_2 \rightarrow 2H_2O$

This creates very high-velocity gas which provides high thrust and relatively ‘high’ specific impulse.

However, A nuclear engine differs greatly from this, instead of getting the energy from inefficient chemical bond breaking, A nuclear engine gets energy from the splitting of an atom, from the strong nuclear force that holds together a nucleus breaking.

A typical Uranium atom undergoing a fission event would generate around 200 MeV (Mega electron volts) much higher than the comparatively minuscule energy released from combustion. (Ref 3)

By passing the propellant either directly through the nuclear reactor, or indirectly around it, the propellant would absorb the massive amount of heat generated from the nuclear fission and accelerate to great velocities, the specific impulse of Nuclear Thermal Rockets is around 2 times higher than normal chemical rockets while retaining a thrust on par with some chemical rockets without the need of carrying an oxidizer.

IV. Nuclear Thermal Rockets Vs Chemical Rockets:

It is to be noted that exhaust velocity is highly dependent on the molar mass of the propellant used along with the temperature of the propellant, the exhaust velocity will be higher if the temperature is high and the molar mass is low. This is why the most efficient chemical engines use Hydrogen as a fuel. (Ref 4 and 5)

As such, A normal nuclear thermal engine may have a lower exhaust temperature compared to the temperatures in the combustion chamber of an oxygen-rich LOX-LH2 engine, but the only propellant in the nuclear thermal rocket is hydrogen. This reduces the molar mass of propellant from 18 to 2, a 9 times decrease. As such the specific impulse of these engines is two times as much. (Ref 4)

Therefore, A typical Solid-Core Nuclear Thermal Rocket would have a specific impulse of anywhere from 850-1000 s, but a gas-core Nuclear Rocket could have specific impulses >3500s. The principle of these engines we hope to discuss in the next part of this paper.

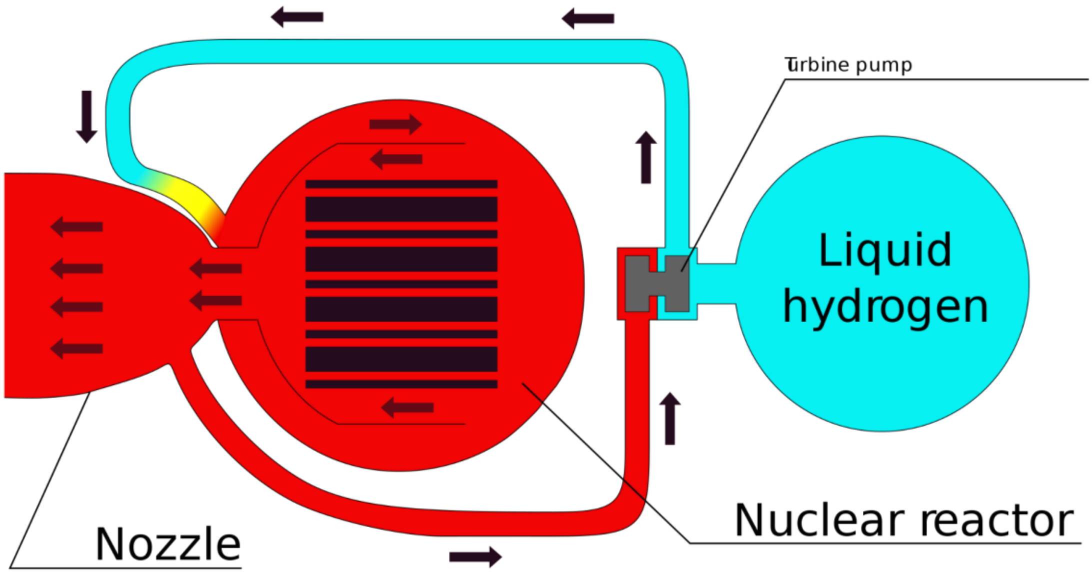


Fig-1 Basic Operation of a SCNTR (Solid Core Nuclear thermal Rocket)
Nuclear thermal rocket. (2022, November 14). In *Wikipedia*.
https://en.wikipedia.org/wiki/Nuclear_thermal_rocket

The Gas-Core Nuclear Rocket Engine:

This type of rocket engine is perhaps the most advanced engine design that operates on the principles of nuclear fission. It can provide massive amounts of specific impulse(>3500 seconds) , while still providing a thrust that can be measured in the hundreds of kiloNewtons, Much higher than ion engines, although lower than most chemical engines, it has almost 10x as much specific impulse. (Ref 6)

The reason why such performance is possible is due to the fact that in the Gas-Core engine, the fissile core, where the fission happens is in the form of a gas, or more accurately, a plasma. The temperatures released from fission heat it up to this temperature. The temperature inside of the suspended uranium plasma reaches almost 50 thousand Kelvin! However, since most of the heat generated is mostly absorbed by the propellant, which when exiting the reactor reaches temperatures of around 10000-12000 Kelvin, and the fact that this heat is only transferred via radiation and fast-moving neutrons, the outer walls do not reach such ludicrous temperatures. (Ref 8)

This results in an exhaust velocity typical of an ion engine (30-50 km/s), with the thrust of a chemical engine, we can achieve extremely fast travel times between planets which we will explore more in the Application part of this paper.

The Reactor Design

A conventional approach for this type of Nuclear Reactor cannot work, as such, we have to consider many things that typically would not matter in a normal nuclear reactor.

First of all, In a nuclear gas core reactor, the uranium plasma where the fission takes place is suspended in the engine, And a nuclear fuel inlet pumps in fissile fuel in the form of Uranium Hexafluoride (UF6) when needed to replenish the fission fuel supply. As such we must think about the confinement of uranium plasma.

Moreover, Thinking about thermal control is also extremely important because of the extremely high temperatures inside the engine.

Surrounding the uranium injection inlet is the hydrogen propellant inlet. This hydrogen will be seeded with an additional gas which we will discuss in the fuel system part of this paper.

Moderators and Reflectors

The neutrons that are emitted from the nuclear fission chain reaction are at extremely high velocities. These neutrons are less likely to split a uranium atom, they rather get absorbed by the nucleus of the atom, rather than initiate a fission event. Thus, they need to be slowed down and that is why reflectors and moderators play a big part in reducing the mass required for criticality and increasing reaction speed for higher temperatures.

For this purpose, an ideal reflector must have a small neutron-absorption area and a large neutron-scattering area (i.e. : It must reflect neutrons much more than absorbing them), along with good thermal conductivity, and high stability. Due to these requirements, beryllium oxide is a good candidate. It has a high melting point of 2,578 °C, which is far more than other reflectors like graphite or heavy water. It also has a high hardness for a reflecting material dealing with lots of high-speed neutrons.[Ref 17]

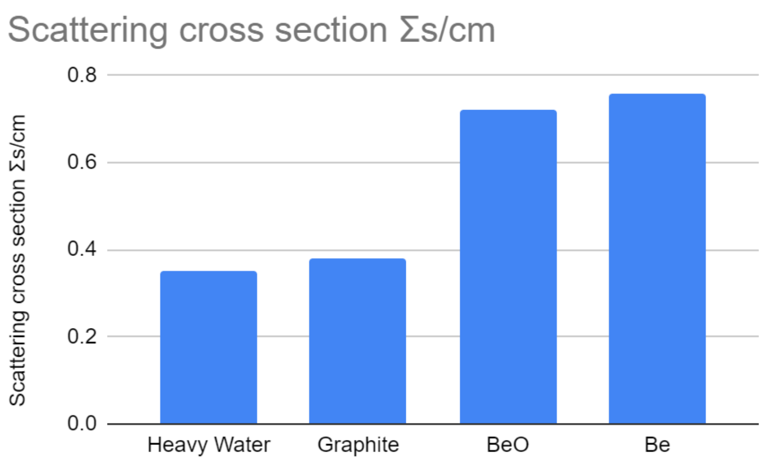


Fig 2, Comparison Of Reflective Capability Of Different Substances, Data From [Ref 16].

Before the reflection of the neutron, it must first be slowed down by a moderator. An ideal moderator must not absorb neutrons, and slow incoming neutrons via collisions. Heavy water makes it suitable to use for this purpose due to its low thermal neutron capture cross-section.

As deuterium oxide absorbs fewer neutrons than hydrogen, the chain reaction can keep on going. It can be kept at a very high temperature too without changing its state of the matter if it is kept under high pressure. Some real-life nuclear reactors have shown that using heavy water moderation reduces the percentage of enriched uranium used in the fuel, as well as highly increasing the number of fission events.[Ref 18 and 19]

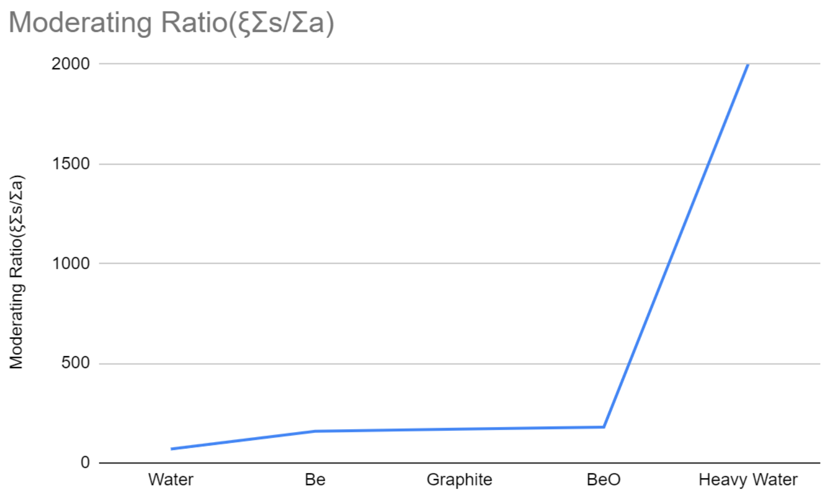
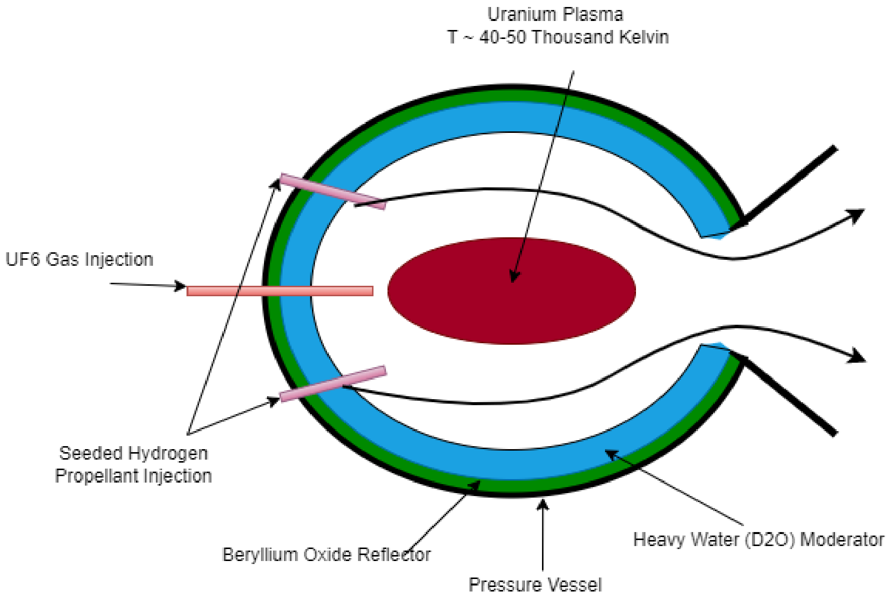


Fig 3, Moderating ratios of possible moderators, from ref [17]



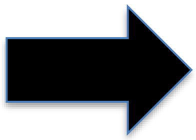


Fig 4, Simplified Diagram of Gas Core Reactor(Spherical Vessel), Radiators and Actual shape of plasma not shown

Fuel Seeding:

In the gas core nuclear reactor, the temperatures of the uranium plasma may reach around 50000 kelvin. At this temperature most of this heat is radiated as ultraviolet radiation, this needs to be absorbed by the propellant so that it heats up and its velocity increases. However, the problem is that hydrogen is optically thin to this wavelength of light, and it cannot absorb it enough. In order to solve this Clark *et al [13]*

suggested utilizing tungsten particles in order to increase the efficiency of absorption. However, these particles would have high molar mass, which would reduce the specific impulse considerably. That is why this paper will focus on the alternative, using noble gasses with low specific heat capacities, almost zero reactivity, and high densities as the additive to hydrogen propellant to increase the efficiency of the engine. [Ref 15]. Moreover, these noble gasses are also widely used in Reaction Control Systems, so we will be able to use them as a seed, and as a propellant for RCS. [Ref 14]

The main reason for choosing the noble gasses was because of their relatively low specific heat capacity when compared to hydrogen, This allows the temperate of the gas and the entire propellant itself to be raised higher with the same amount of energy, and as the exhaust velocity is a function of the temperature of the propellant, this greatly increases our specific impulse for the rocket. Moreover, a noble gas wouldn't react with the hydrogen or the reactor walls extending the longevity of the nuclear reactor. Though the addition of noble gas increases the molar mass of the propellant slightly (As we are only considering the noble gas as 5% mass of the propellant), this decreases the specific impulse very slightly, but it is offset by the massive increases in the absorption of heat. (Ref 11)

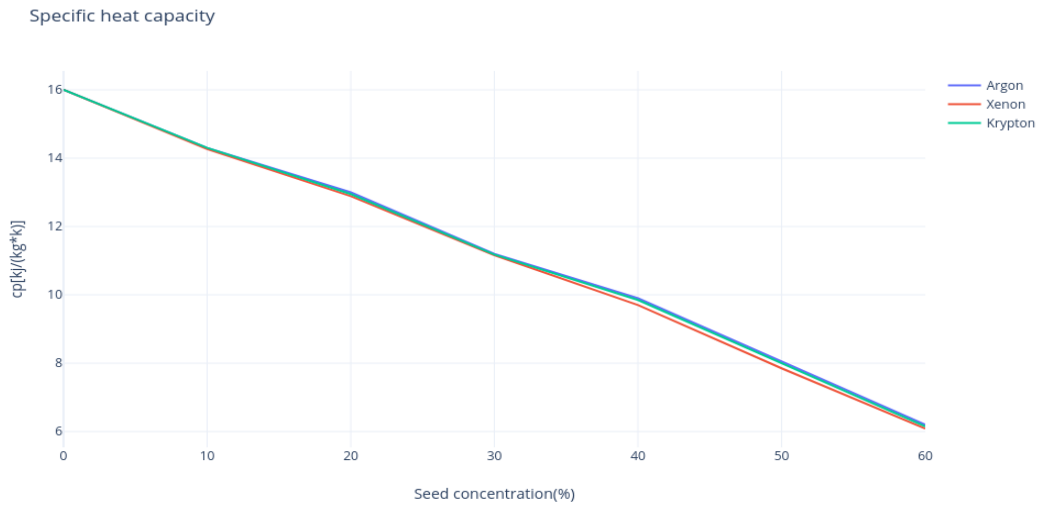


Fig 5, Specific Heat Capacity of different seeded propellants, data from [Ref 12]

We have decided to utilize Argon (Ar) as the noble gas in our system. The primary reasons for this are that first of all it is the most abundant noble gas, secondly, it has one the lowest masses of the noble gasses behind xenon and helium and thirdly the most research and simulations have been done on Argon, making it a more reliable source. Another advantage of using this substance in our propellant is that it increases the density of the propellant allowing us to keep more mass in the same area, greatly increasing our DeltaV. (Ref 12)

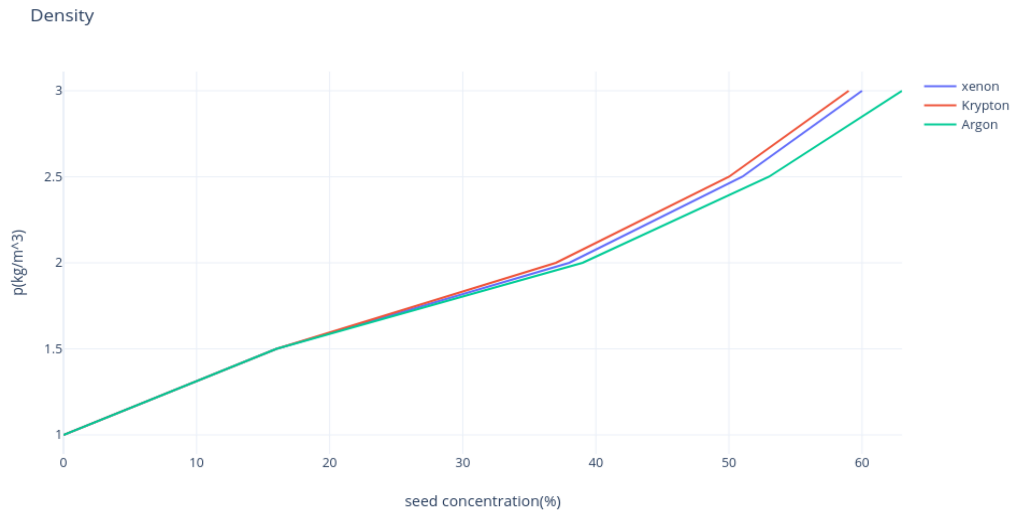


Fig 6, Density of seeded propellants, Data from [12]

On the confinement of Uranium plasma:

One of the biggest hurdles in Gas Core engines is the confinement of uranium plasma, Since the hydrogen and the uranium plasma are in direct contact with the engine, Some of the fissile material may exit the reactor, and 'leak'. To prevent this leakage of Uranium plasma and to ensure that it is confined inside the reactor many methods have been developed. Mainly focusing on the utilization of Flow Hydrodynamics to create a sort of vortex in the engine where the nuclear fuel is contained.

Initially one might consider the application of a magnetic field in order to contain the super hot ionized Uranium Plasma, however utilizing just a magnetic field to retain the plasma is infeasible, this is because of the incredibly high pressures present inside of the plasma(>400 Atm), the magnetic fields would also need to be incredibly strong, upwards of 10 Tesla in order to eliminate all mixing. The weight and size of the magnets required to produce a field that strong would be very detrimental to the design of the engine and the rocket. (Ref 8)

As such most gas core reactor designs have the gaseous core in a vortex inside the reactor, 3 different shapes of the core were tested: Cylindrical, Toroidal, and Counterflow toroidal. Research into these shapes proved that the counterflow toroidal shape would minimize nuclear fuel losses the most. (Ref 9)

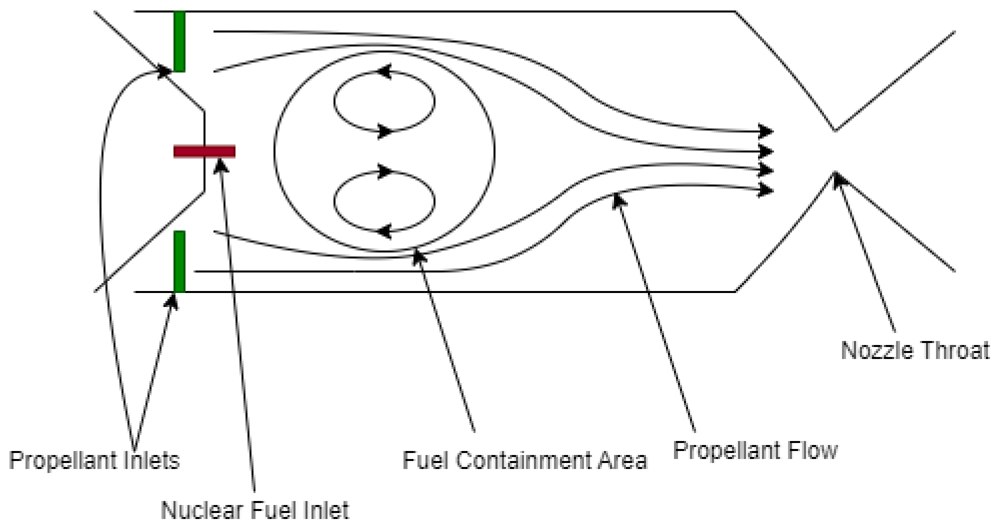


Figure 7; Simplified counter flow toroidal confinement diagram (Cylindrical Vessel)

The formation of the vortex is very complex and not fully understood, but after it has been formed the uranium fuel is injected into the engine which settles at the center of the vortex, starting the fission reaction and superheating the uranium into a plasma. Though this method needs more experimental testing and research, it is one of the most promising methods of reducing the fuel loss rate to ~1% (To maximize the amount of time for which the fuel 'burns') which is needed for the engine to be practically feasible. (Ref 7 and 6)

Though a magnetic field to contain the entirety of the plasma is not feasible, A magnetic nozzle could be used to stop the uranium plasma from exiting the engine. (Ref 10) In typical magnetic nozzles, the charged plasma ions are guided via magnetic fields out of the engine, but due to the fact that magnetic field lines form a closed loop a mechanism known as plasma detachment is used to detach the ions from the magnetic field lines, but if this mechanism is not present, the plasma would simply flow back into the engine. For most cases this is bad, however for a Gas Core Open cycle engine, this would be perfect to stop the uranium plasma from exiting the engine, However, more research is required on this topic.

V. Thermal Control In The Engine

The temperatures of the uranium plasma inside the gas core engine are going to exceed 50,000 K due to the massive fission energy released during the chain reaction, though the outer walls are only heated to a fraction of that temperature. To keep the temperatures of the walls of the reactor from melting and at a suitable temperature, a system to remove heat from the system must be introduced.

A space radiator could be used, and the outer walls of the reactor could be connected via heat channels to radiators to radiate the generated heat out into space. We have decided upon the material of silver fluorinated ethylene propylene.

Silver fluorinated ethylene propylene has a solar transmittance of 96%. It is also more transparent and has low gas permeability and porosity than other materials like PTFE(Polytetrafluoroethylene). It is also very non-reactive and has low friction. Silver FEP even has a surprisingly high stress-crack resistance and is somewhat more rigid, with a hard tensile strength. [20]

Another method of cooling would be provided by the moderator, deuterium oxide. As deuterium oxide is already flowing around the combustion chamber to slow the neutrons generated from fission, it will be able to absorb the heat. After this, we can pump the heated deuterium oxide into a turbine that powers the pump that flows Hydrogen Propellant into the reactor, hence cooling the walls AND solving a plumbing issue.

The Application of Gas-Core Rocket:

Very simply, the gas-core nuclear rocket cannot be used in the atmosphere. The leaking of the uranium plasma will result in lots of particles that emit radiation going into the atmosphere and causing major damage to the human (And all other forms of life) populace.

Instead, it is better to utilize the gas-core rocket as a space-only engine. We envision a sort of Nuclear Ferry model, A large interplanetary spacecraft that is constructed in space that cannot go into the atmosphere but rather is designed to maximize the efficiency of its engine, carry large amounts of fuel along with having a big habitation space with new innovations to ensure the happiness and safety of the crew during long voyages in space.

Such a spacecraft would be constructed in Low Earth Orbit, using multiple launches. It would serve as a sort of 'bus', spacecraft would launch from earth and dock with it, the ferry as we shall call it now would be able to carry multiple spacecraft and the crew would be stationed in its habitation quarters which would use advanced radiation shielding to protect the crew.

The ferry would then ignite its gas core engine for a single burn, either a Trans Lunar Injection burn or a Trans Mars Injection burn. The burn would last much longer than normal TLI or TMI burns in order to maximize flight speed and minimize the duration of travel. Once reaching the destination, either the moon or mars. The ferry would fire its engines again for the second time to circularize around the moon or mars.
The time taken to coast between earth and mars depends on the burn time but could be as low as 3 months!

The spacecraft docked with the ferry would then undock and make its way to a space station, or land on the planet. The ferry would then wait for spacecraft from the moon or mars to dock with it before making its way back to earth. Again only making 2 burns to return to earth.

Once back in earth orbit it would wait for resupplies. The minimization of burn minimizes the amount of Uranium fuel lost while at the same time taking advantage of the high impulse and high thrust of these engines.

For the calculation of Specific Impulse and Thrust, We shall take the mass flow rate to be 4.5 kg/s, 4 kg/s of hydrogen flow, and 0.5 kg/s of argon flow. Along with this, we shall take the exhaust velocity to be ~ 35 km/s which is reasonable if the exhaust's temperature is around ~11 thousand kelvin.

With these numbers, we can estimate the specific impulse to be 3569s, This large number is usually only achieved by ion engines and would have almost 8x the impulse of even the most efficient chemical engines.

The thrust would come out as 157.5 KiloNewtons, around half of the thrust of solid core nuclear engines but still leagues above the thrust of ion engines.

VI. Conclusion:

Humankind has always yearned to explore the great beyond, and gas-core nuclear engines might just be the best method for space propulsion to get to mars and the moon which is currently possible with our technology. These gas-core engines still have some problems before they can work, but with more research can easily go into the realm of physical tests. Their impulse would be ~8x as much as the most efficient chemical engines while having a thrust measured in the hundreds of KiloNewtons. It is quite feasible to utilize these engines in the nuclear ferry model eliminating the need to launch a complete interplanetary spacecraft each time one needs to go to mars or the moon. This could be the next step in the next phase of our civilization, to make it an interplanetary one.

References

[1] Nasa(For General Rocket Principles)
[2] Cho, S. J., Lee, J., Lee, Y. S., & Kim, D. P. (2006). Characterization Of Iridium Catalyst For Decomposition Of Hydrazine Hydrate For Hydrogen Generation. Catalysis Letters, 109(3-4), 181–186. Doi:10.1007/S10562-006-0081-3
[3] Https://Chem.Libretexts.Org/Bookshelves/Physical_And_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_And_Theoretical_Chemistry)/Nuclear_Chemistry/Fission_And_Fusion/Fission_And_Fusion
[4] Http://Large.Stanford.Edu/Courses/2011/Ph241/Hamerly1/
[5] Https://Www.Fxsolver.Com/Browse/Formulas/Exhaust+Gas+Velocity
[6] Poston, D. I., & Kammash, T. (1996). A Computational Model For An Open-Cycle Gas Core Nuclear Rocket. Nuclear Science And Engineering, 122(1), 32–54. Doi:10.13182/Nse96-A2854
[7] Thode, L., Cline, M., And Howe, S., "Vortex Formation And Stability In A Scaled Gas-Core Nuclear Rocket Configuration," Journal Of Propulsion And Power, Vol. 14,No. 4, 1998, Pp. 530– 536
[8] Koroteev, A., & Son, E. (2007). Development Of Nuclear Gas Core Reactor In Russia. 45th Aiaa Aerospace Sciences Meeting And Exhibit. Doi:10.2514/6.2007-35
[9] Frisbee, R. H. (2003). Advanced Space Propulsion For The 21st Century. Journal Of Propulsion And Power, 19(6), 1129–1154. Doi:10.2514/2.6948
[10] Viswanathan, Krishnamurthy. (2013). Liquid Oxygen Augmented Gas Core Nuclear Thermal Rocket.
[11] D. Nikitaev, (2019) Seeding Hydrogen Propellant In Nuclear Thermal Propulsion Engines,Theses, 366
[12] A L. Aureon, And L D. Thomas (2019), Nuclear Thermal Propulsion And Vehicle Scaling And The Importance Of Densified Propellant, Aiaa Propulsion And Energy 2019 Forum, Doi:10.2514/6.2019-3942
[13] J. W. Clark And G. H. Mclafferty, "Summary Of Research On The Nuclear Light Bulb Reactor," United Aircrajt Research Laboratories, 1971.
[14] Nasa, "Ion Propulsion," Nasa, Cleveland, Oh, 2016
[15] V. Zagarola And J. A. Mccormick, "High-Capacity Turbo-Brayton Cryocoolers For Space Applications," Science Direct, Vol. 46, Pp. 169-175, 2006.
[16] Dawahra, S., Khattab, K., & Saba, G. (2015). Investigation Of Beo As A Reflector For The Low Power Research Reactor. Progress In Nuclear Energy, 81, 1–5. Doi:10.1016/J.Pnucene.2014.12.001