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Nuclear Propulsion Development Plan

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Abstract: ***The objective of this paper is to find alternative methods of propulsion. A nuclear fission incorporated engines can be installed in aerial vehicles. With this we could achieve higher Mach velocities and highly efficiency. This Nuclear Power can be produced by innovative methods such as nuclear thermal engine and fission fragmented rocket engine. Liquid hydrogen can be used as working fluid which will be heated to high temperatures and thereby expanded through a converging nozzle leading to thrust production in nuclear thermal engine. The Fission fragmented rocket engine (FFRE) design can directly harnesses nuclear fission products for thrust, which are normally trapped inside a reactor, as opposed instead of using a separate fluid as working mass. This design allows the heavy fission products to escape from the reactor, travelling at up to 5% of light speed theoretically producing thrust at over 200 times better than electric engines. Electricity needs of the aerial vehicle can also be met through nuclear power whereby using a fraction of heat generated by fission in combination with thermoelectric and thermionic generators.***

Keywords: Nuclear Propulsion, Nuclear reactor, Alternate form of propulsion, Electricity generation, hypersonic rockets

1. Introduction

We know that World population is increasing rapidly. One day, the mother EARTH may not be sufficient for us to survive because of its limited resources and land. So there is a need for exploring space and finding possibilities of life. But achieving such high speeds with current propulsion systems is impossible. So we should focus on SUPER HYPERSONIC ROCKETS.

In this paper, I am going to describe the development of nuclear propelled engines which could attain greater mach speeds.

2. Main Section

2.1 Nuclear Thermal Rocket

- A Nuclear Thermal Rocket (NTR) creates thrust by heating and expanding a working fluid, such as hydrogen, a fusion fuel, in a nuclear reactor.
- An NTR engine has twice the efficiency of the best chemical engines due to the high energy level produced by the nuclear reactions when compared to the combustion in chemical thrusters.
- The exhaust of chemical rockets are constrained by the chemical reaction, but in an NTR, the heat source is not based on the propellant, so an NTR can use a low molecular weight propellant, such as hydrogen, to improve performance. The high specific impulse (Isp) levels of an NTR rocket offer opportunities for missions with shorter trip times and greater payloads that those that can be accomplished using only chemical propulsion.
- The reactor used in an NTR vehicle operating in the "Bimodal" mode, can be used to create electrical power when not being used to produce thrust. A Tri-modal system includes an afterburner-style operation cycle in which liquid oxygen (LOX) is injected into the nozzle for increased thrust (and therefore, lower Isp).
- Nuclear Thermal Rocket Propulsion is not a new technology. NTR dates back to the NERVA program in the 1960s. The NERVA engine was a solid-core design, which is the traditional and simplest design to make. Other advanced design concepts include a liquid-core and a gas-core reactor.

2.1.1 Working

- The propellant, usually hydrogen, is stored as a liquid in the tank. The pump forces the propellant through the piping system the surrounds the nozzle and rocket motor.
- A set of turbo pumps feed liquid hydrogen into the engine. Most of the hydrogen flow enters the top of the engine enclosure, but part is split off to feed a heat exchanger on the walls of the rocket nozzle, thereby cooling the nozzle and preheating the hydrogen. The turbo pumps provide the very large pressure required to keep fuel flowing against the back pressure of the engine.
- The hydrogen is fed into the reactor core, which has a matrix of longitudinal channels in which the hydrogen is heated to temperatures in excess of 2500° K. The reactor core is surrounded by a neutron reflector, which allows the use of smaller amounts of fissionable material in the reactor. The propellant becomes heated and expands to a gas, at the same time limiting the temperature of the shell and nozzle.
- Once the hydrogen is heated by the reactor, it is exhausted through the nozzle, attaining an exhaust velocity as large as 10 km/s or more. The propellant accelerates out the nozzle to provide thrust. Some of the heated fluid is used to turn the turbine driving the pump.

2.1.2 Calculations

Calculations performed as part of the space nuclear propulsion program show that a first generation nuclear thermal rocket will allow a performance improvement of between 50 and 400 percent over the best conventional rocket motors. Performance of a nuclear thermal engine:

a) For any given thrust, the amount of power that needs to be generated is defined by $P = T * Ve / 2$

- Where,

  T is the thrust and Ve is the exhaust velocity.

  Ve can be calculated from the specific impulse, Isp, where

  $Ve = Isp * gn$

(When Isp is in seconds and gn is the standard, not local, acceleration of gravity)

- Using the formula above, we can calculate the amount of power that needs to be generated, at least given extremely efficient heat transfer. It is seen that that power is directly proportional to the specific impulse. Since according to our data collected, the average impulse generated by chemical engine is seven hundred seconds and one million seconds for NTR, NTR produces more power.

b) If the fuel is expelled at a rate -dm/dt with speed Ve, a corresponding recoil force F = -Ve*dm/dt , acts back the rocket, accelerating it in a direction opposite the exhaust flow.

- Integrating Newton's Second Law over time, one finds a relation between the velocity boost and the mass loss: Δv = vex log(m_o/m)
- Here m_o is the launch mass of the rocket (payload plus fuel), while m is the mass of the payload.
- For a fixed exhaust velocity and payload mass, the launch mass increases exponentially with Δv.

c) In an ideal rocket, the conversion efficiency is 100%, and the exhaust velocity is: Ve = (2E/m)1/2

- Where, E/m is the energy density – the energy per unit mass released in the chemical reaction. Naturally, we want to pick fuels that maximize the energy density; hence hydrogen and oxygen are aare the best options.
- These set a limit to the exhaust velocity of Ve < 4.5 km/s. This is not good news for deep-space explorers. With an exhaust velocity limited to 4.5 km/s, the launch mass of a moon rocket will be at least 15 times the size of its payload, and for a Mars rocket, the ratio is around 100:1. Missions to the outer planets are staggeringly more expensive.
- The limits in the rocket equations stem from fundamental laws of physics – namely, energy and momentum conservation. No amount of hard work or ingenuity can circumvent them. Hence deep space travel requires something beyond conventional chemical rockets.

d) The Nuclear Thermal Rocket consists of a high-temperature nuclear reactor with a series of thin channels for the propellant. The nuclear reactor is usually run as hot at around 2500-2800 °K, just below the melting point of the fuel. Hydrogen gas is used as a propellant because its low molecular mass enables it to be expelled at very high speeds. The propellant is sent through the channels and heated to the temperature of the reactor, and thereafter expelled through the rocket nozzle. Using the heat capacity of hydrogen, it is easy to compute the specific enthalpy h of the fuel, and consequently the exhaust speed Vex, through Bernoulli's Law
Ve = √(2h)

For a reactor operating at 3000 °K, the propellant will be expelled at a speed of 10 km/s. This is far from the theoretical maximum of 5,000 km/s, but nevertheless is more than twice the exhaust speed of the best conventional rockets. As per the logarithm in the rocket equation, this doubling works substantial changes in the mass ratio of lift-off to payload mass; for a nuclear-powered lunar mission, the mass ratio is reduced from 15:1 to around 4:1, while for a Mars mission, it drops from 100:1 to 10:1.

e) Also, the velocity of the rocket propellant scales as: Ve ~ √(T/m), where T is the propellant temperature and m is its molecular mass.

- In a chemical hydrogen-oxygen rocket, T ~ 6000 °K and m = 18 amu.
- For a nuclear rocket, the temperature is halved (T ~ 3000 °K), but the mass drops by a factor of nine (m = 2 amu), so the quotient increases by about a factor of four, doubling the exhaust speed.
- The mass of hydrogen used in NTR is much lower than the hydrogen/oxygen mix in for example the Rocketdyne J-2, where only about 1/6 of the mass is hydrogen. Since liquid hydrogen has a density of about 70 kg/m³, the value of m_o in NTR is lower, again concluding to higher Ve.

2.2 Fragment-Fission Rocket Engine

- The fission-fragment rocket is a rocket engine design that directly harnesses hot nuclear fission products for thrust, as opposed to using a separate fluid as working mass.
- The products of fission reactions are normally trapped inside a reactor, producing heat that is converted to electricity. This electricity, stepping through the inefficiencies, is used to produce thrust. The design of a FFRE, instead, allows these same heavy fission products to escape from the reactor, traveling at up to 5% of light speed. Theoretically, heavy fission products traveling at up to 5% of light speed produce thrust at a specific impulse of one million seconds (over 200 times better than electric engines). The efficiency of a FFRE, as measured by the quantity of fission fragments that escape as a beam rather than remain inside the reactor and produce waste heat, in this study was about 11%.

2.2.1 Working

- A conventional nuclear reactor contains large fuel rods that last for years containing a fissionable element (Uranium 235 for example) that is bound in a metal matrix, clad with a coating, and surrounded with coolant that wicks off the heat and converts this heat to electricity. The radioactive fission fragments collide with other atoms in the rod, accumulating and causing the fuel element to eventually —poison (halt) the fuel fissions.
- To overcome this poisoning effect, the core needs an excess of nuclear material beyond that required for criticality. Nonetheless, these highly radioactive fuel rods must be eventually replaced in order to continue operation.
- Unlike the fuel rods of a typical reactor, the FFRE reactor core consists of sub-micron sized fissioning dust grains that are suspended and trapped in an electric field. The amount of dust must be continuously replenished. The fission fragments that remain in the core collide with dust grains. These collisions, along with the thermal energy released by the fission events, create intense heat in the dust.

- Since there is no core cooling flow, the power of the FFRE is limited to the temperature at which the dust is able to radiatively cool without vaporizing. The cavity in which the dust resides is open to the vacuum environment; the loads on the engine are thermal, not pressure.
- Surrounding the dusty core is a mirror finish heat shield that reflects 95% of the thermal energy. The residual heat is wicked to a radiator and the heat rejected to space. The moderator maintains criticality of the core by converting fast fission event neutrons into slower speed thermal neutrons (cooling) and reflecting them back into the core. This moderator also needs a radiator to maintain its operating temperature.
- A hole in the moderator allows a fraction of the fission fragments to escape as directed by surrounding intense magnetic fields. The performance and attributes of the FFRE depend significantly on the geometric shape.
- The moderator is protected from the core thermal radiation by an actively cooled Carbon-Carbon heat shield and additionally is cooled by active pumped cooling flow. This coolant flow is first passed through a Brayton power conversion system to extract electrical power for general spacecraft use. Mass of the moderator subsystem is about 52mT including 30% Mass Growth Allowance(MGA)

2.2.2 Electricity Generation

Electrical power is also required in the aircraft or rocket to run the electric instruments, provide cabin lighting and to power many other systems. This electricity is also obtained from the fuel engine in a conventional aircraft. We have proposed methods for direct conversion of nuclear energy to thrust but the same nuclear reactor can also be used to meet the electricity requirement with the help of another mechanism.

1. <u>Photovoltaic cells</u>

- A system that directly converts nuclear energy into electricity would be cheaper than current nuclear conversion technology.
- For years, researchers have been in search of an economically feasible method of converting nuclear energy directly into electricity.
- Current nuclear technology has an intermediate thermalization phase between the nuclear reaction and when the energy is converted to electricity. This phase reduces the efficiency of the energy conversion process.
- Based on the idea that photovoltaic cells can be used for nuclear fission detection, it is possible to harness electricity from nuclear fission by these cells.
- A system known as Radioisotope Energy Conversion System (RECS) introduced. In the first step of the process, the ion energy from radioisotopes is transported to an intermediate photon generator called a fluorescer and produces photons, which are the basic units of light. In the second step of the process, the photons are transported out of the fluorescer to photovoltaic cells, which efficiently convert the photon energy into electricity.
- The nuclear light bulb was based on the Photon-Intermediate Direct Energy Conversion (PIDEC).
- PIDEC converts the high-grade ion energy to photon energy.

2. <u>Thermocouples and Thermistors</u>

- A mechanism similar to RTG can be used. A radioisotope thermoelectric generator (RTG, RITEG) is an electrical generator that obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples.
- RTGs have been used as power sources in satellites, space probes and unmanned remote facilities. RTGs are usually the most desirable power source for robotic or unmaintained situations needing a few hundred watts (or less) of power for durations too long for fuel cells, batteries, or generators to provide economically, and in places where solar cells are not practical. Safe use of RTGs requires containment of the radioisotopes long after the productive life of the unit.

2.2.3 Working

- The design of an RTG is simple by the standards of nuclear technology: the main component is a sturdy container of a radioactive material (the fuel). Thermocouples are placed in the walls of the container, with the outer end of each thermocouple connected to a heat sink. Radioactive decay of the fuel produces heat which flows through the thermocouples to the heat sink, generating electricity in the process.
- The thermocouple is made of two kinds of metal (or semiconductors) that can both conduct electricity. They are connected to each other in a closed loop. If the two junctions are at different temperatures, an electric current will flow in the loop.

2.2.4 Material Requirement

- The performance of a thermal nuclear engine is limited by the high temperature strength of solid materials.
- Thermal insulation materials for sharp leading edges on hypersonic vehicles must be stable at very high temperatures (near 2000 degrees C). The materials must resist evaporation, erosion, and oxidation, and should exhibit low thermal diffusivity to limit heat transfer to support structures.
- Ultra-High-Temperature Ceramics (UHTCs) are composed of zirconium diboride ($ZrB2$) and hafnium diboride ($HfB2$), and composites of those ceramics with silicon carbide (SiC). These ceramics are extremely hard and have high melting temperatures (3245 degrees C for $ZrB2$ and 3380 degrees C for $HfB2$). When combined, the material forms protective, oxidation-resistant coatings, and has low vapor pressures at potential use temperatures.
- Cermet materials also offer several advantages such as retention of fission products and fuels, thermal shock resistance, hydrogen compatibility, high conductivity, and high strength.

3. Conclusion

If this nuclear propelled rocket comes into existence, the frequency of space travels increases and the possibility of establishing colonies mars would be possible.

4. Author’s Note

Researches on reducing the radioactive wastages and the material selection should be done in parallel to this project in order to tackle radio activity. Where there is no risk, there is no life.

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Author Profile

Mr. Rahul Munagala, the author of this paper is now pursuing B-Tech in Aerospace Engineering from SRM University, Chennai, India. He was born on June 3rd, 1994 at Nalgonda in Andhra Pradesh State, India. He finished his schooling with an aggregate of 94.3 % and higher secondary with an aggregate of 92 %. He is known for his passion in Aerospace Engineering. He would like to do makeup his career in research and would dedicate himself for that. He has done 2 internships till date .First one on Gas turbine engines at Hindustan Aeronautics Limited and the other at Bharat Dynamics Limited on 'Akash Missile system ' . He has presented 2 papers on nuclear propulsion. The topic is Alternate propulsion Technology - Nuclear Upgrade and presented at ' International Conference on Advances in Engineering and Technology ' in Goa. He is now working as Descent Control system designer and developer as well as Pitcrew Officer in balloonsat Project. He is also working as Mechanical Systems Engineer in Team ' Space Rodeos ' from SRM University which is working on European Rover Challenge.