NUCLEAR PROPULSION CHOICES FOR SPACE EXPLORATION

4/4/2012

1. INTRODUCTION

Nuclear power systems are currently in use for space applications as heat sources and for electrical power generation. The use of nuclear propulsion is contemplated for future space missions over long distances with relatively large payloads.

The first use of nuclear-fission for propulsion was discussed in 1942 just after the completion of the first nuclear reactor concept, Chicago Pile number 1, CP1 was achieved. By 1946, studies were performed on heating low-molecular weight propellants such as hydrogen by a fission reaction. The initial studies were promising for the future of nuclear propulsion rockets and aircraft. However the available materials as wells as lack of information on material properties limited the feasibility of the designs.

About this time, the USA Air Force established the Nuclear Energy for Propulsion of Aircraft (NEPA) project which later gave way to the Aircraft Nuclear Propulsion (ANP) program. In 1959, the first nuclear-rocket reactor test was performed designated as Kiwi-A (Fig. 1).

In 1961, the Nuclear Engines for Rocket Vehicle Applications (NERVA) began building nuclear rocket engines under the direction of the Atomic Energy Commission (AEC) and the National Aeronautics and Space Administration (NASA).

The rockets built by the NERVA program were more powerful than the largest and most powerful chemical rockets of the time with a smaller size. Despite the promising results, NASA cut funding for the NERVA program in 1973.

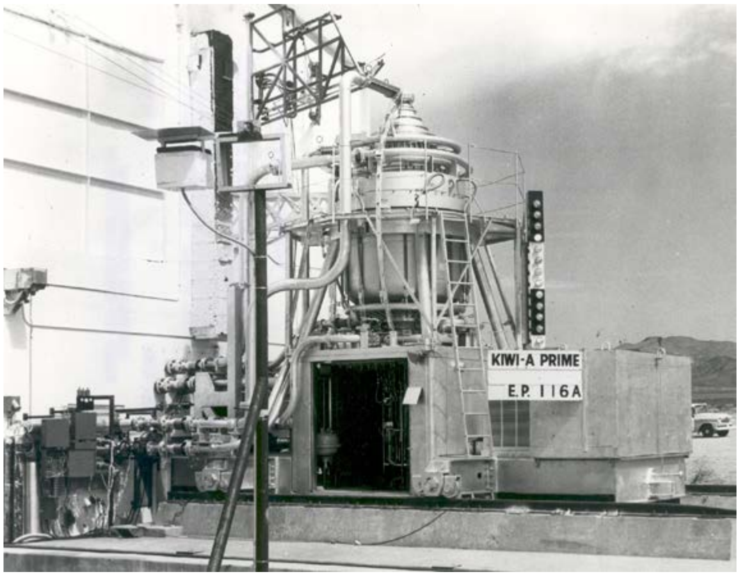

Figure 1. Kiwi-A reactor c. 1959. Source: NASA.

Nuclear power has also made an impact on space exploration in other areas than propulsion. Radioisotope Heater Units (RHU) provide heat from a radioactive decay for electronics and other equipment in the cold of space. Nearly all space missions traveling further than the orbit of Mars have incorporated RHUs. Radioisotope Thermoelectric Generators (RTGs) convert thermal energy from radioactive decay into electrical power for satellites or unmanned space probes. RTGs provide power for a longer period of time than fuel cells or batteries and can operate in deep space where solar cells are not viable [1].

The future of nuclear propulsion is expanding past the designs of the NERVA rockets to more advanced systems. NASA's Prometheus program is developing a nuclear powered ion thruster rocket for long distance and duration missions while carrying a relatively heavy payload, which is shown conceptually in Fig. 2. At the Los Alamos National Laboratory, testing is being performed on rocket designs which utilize a gas core rather than the solid reactor core of the NERVA rockets. These designs are thought to have 3-4 times the thrust of solid core nuclear propulsion systems.

Figure 2. Conceptual design of the Prometheus program (NASA).

2. SPECIFIC IMPULSE

Rocket propulsion combines the principles of mechanics, thermodynamics and in the present case, nuclear science. Propulsion is achieved by applying a force to a vehicle to accelerate it. Alternatively it involves the application of a steady velocity against a resisting force. The propulsive force is achieved by ejecting a propellant at high velocity from a nozzle creating thrust.

The *total impulse* I_t is considered as the time integral of the thrust force F(t):

$$I_t = \int_0^t F(t)dt \tag{1}$$

The time t is the burn time of the rocket, and the thrust force F(t) is a function of time.

In rocket engines, the propellant or working fluid is carried aboard the vehicle being propelled. Accordingly, the duration of the mission is limited by the mass of the propellant carried. This imposes a premium on the rocket's *specific impulse* I_s defined as the ratio of the total impulse per unit weight w of the propellant:

$$I_s = \frac{\int_0^t F(t)dt}{w} \tag{2}$$

where the total weight of the propellant in terms of the mass flow rate is given by:

$$w = g_0 \int_0^t \dot{m}(t)dt \tag{3}$$

where g_0 = 980.66 cm/sec^2 or 32.16 ft/sec^2, is the gravity acceleration at sea level.

For constant thrust force F and propellant flow, this equation can be simplified as:

$$I_s = \frac{F.t}{g_0 m_p} = \frac{F}{g_0 \dot{m}} = \frac{F}{\dot{w}} = \frac{I_t}{w} = \frac{v_e}{g_0} \tag{4}$$

where F is the thrust, $\dot{m}$ is the exit mass flow rate, v_e is the effective exhaust velocity and g_0 is the acceleration due to gravity at the Earth's surface.

This equation identifies the specific impulse as the total impulse F.t, per unit weight of the propellant g_0 m_p. The specific impulse I_s is also called the *specific thrust* since in fact it is the total thrust I_t per unit weight w of propellant.

The unit of the specific impulse in the Système International (SI) system of units is:

$$\frac{\text{Newtons}}{\frac{\text{m}}{\text{sec}^2}.\frac{\text{kg}}{\text{sec}}} = \frac{\text{kg}.\frac{\text{m}}{\text{sec}^2}}{\frac{\text{m}}{\text{sec}^2}.\frac{\text{kg}}{\text{sec}}} = \text{sec}$$

The specific impulse is important for a number of reasons. First, it is a simple parameter indicating rocket efficiency and thus a good initial comparison of engine designs. Secondly, the specific impulse allows for "sizing" of an engine. The thrust is determined by the payload and engine weight, so if the specific impulse is known, then the propellant mass can be determined.

3. ROCKET EQUATION

The Tsiolkovsky ideal rocket equation gives a Δv (typically in km/s) value for an equivalent velocity change for a rocket trajectory and is given by [2]:

$$\begin{aligned}\Delta \mathrm{v} &= \mathrm{v}_e \ln\left(\frac{M_i}{M_f}\right) \\ &= \mathrm{v}_e \ln\left(\frac{M_p + M_f}{M_f}\right) \\ &= \mathrm{v}_e \ln\left(\frac{M_p}{M_f} + 1\right)\end{aligned} \tag{5}$$

where M_i is the intial mass, M_f is the final mass and M_p is the propellant mass.

The $\Delta \mathrm{v}$ is a parameter for a given space mission. For instance an Earth to Low Earth Orbit (LEO) mission has a typical $\Delta \mathrm{v}$ around 10 km/s. Rearranging and using the definition of I_s gives:

$$\frac{M_p}{M_i} = 1 - \exp\left(\frac{-\Delta \mathrm{v}}{I_s g_0}\right) \tag{6}$$

For a typical *chemical* rocket going into LEO with I_s = 500 s, g_0 = 9.8 m/s^2 and $\Delta \mathrm{v}$ = 10 km/s, the ratio of propellant to initial mass is calculated as:

$$\begin{aligned}\frac{M_p}{M_i} &= 1 - \exp\left(-\frac{10 \times 10^3}{500 \times 9.8}\right) \\ &= 1 - e^{-2.04} \\ &= 0.867\end{aligned}$$

So for this situation, about 87 percent of the mass of the rocket must be the propellant.

For a *nuclear* rocket, a value of I_s = 1,000 yields:

$$\begin{aligned}\frac{M_p}{M_i} &= 1 - \exp\left(-\frac{10 \times 10^3}{1,000 \times 9.8}\right) \\ &= 1 - e^{-0.204} \\ &= 0.184\end{aligned}$$

It can be seen that by increasing the specific impulse, one can decrease the percentage of total mass required for the propellant, allowing for an increased payload for the same mission.

4. NUCLEAR PROPULSION DESIGNS

In a chemical rocket engine, a propellant composed of fuel and an oxidizer undergoes an exothermic reaction heating the gases to high temperatures [3, 4].

The propellant passes through a nozzle providing thrust to the rocket in the opposite direction that the propellant gas is exhausted. The most efficient liquid fuel propulsion rockets today have a specific impulse approaching 500 s but typical values are 200 – 400 s.

Nuclear propulsion systems operate by heating a low-molecular weight propellant using the heat from a nuclear reaction rather than a chemical reaction of the propellant itself. Using nuclear propulsion, the propellant can be composed of pure hydrogen which results in very high I_s due to the low molecular weight. Hydrogen is also a good choice for a propellant for nuclear propulsion because of its low neutron absorption cross-section and relatively low cost and ease of handling.

A solid core Nuclear Thermal Rocket (NTR) operates at a temperature of approximately 2,200 °C and may be one of several concepts: particle beds, pellet beds, wire core and foil reactors.

These temperatures are lower than those achievable by chemical rockets, however the use of pure hydrogen allows for specific impulses approaching 1,000 s which is twice that available for the best chemical rockets.

A gas core NTR is expected to increase the specific impulse by increasing the temperature of the propellant. In this design, the propellant mixes with the fuel which operates in a gaseous state.

The temperature is limited by the containing wall melting temperature. The specific impulse generated by this rocket design is thought to be around 1,500 – 3,000 s.

The increase in specific impulse is a significant advantage for long distance space travel with a high mission Δv. Table 1 shows the Δv for one-way missions between Earth and select planets in our solar system.

Table 1: Missions to solar system planets.

Planet	Mean Orbital Radius astronomical units [au]	Δv [km/s]
Mercury	0.39	9.89
Venus	0.725	2.70
Mars	1.52	2.38
Jupiter	5.2	8.81
Saturn	9.5	10.27

Table 2: Comparison of Characteristics of Rocket Propulsion Systems.

Concept	Specific Impulse [sec]	Mars trip Duration [days]	Working Fluid	Fuel	Temperature [K]
Chemical-solid or liquid bipropellant	200-400		H_2 and O_2	N_2H_4	2,773-4,573
Liquid monopropellant	180-240		N_2H_4	N_2H_4	1,273-1,573
Solar heating	400-700		H_2	-	1,573
U <u>Nuclear Solid Core</u>					
Nerva	825-850	434		Duplex	2,270
Enabler	925-1,080			UC-ZrC-C	2,700-3,300

Cermet	832			UO_2-W	
Wire core	930			UN-W	3,030
Advanced Dumbo	-			UC-ZrC	2,700-3,300
Pellet bed	998			UC-TaC	3,100
Particle bed	1,000-1,200	434		UC-ZrC	3,000-3,500
Low pressure	1,050-1,210			UC-ZrC	3,000-3,600
Foil reactor	990			UO_2	2,700-3,400
U Nuclear Liquid Core					
Liquid annulus	1,600-2,000				3,000-5,000
Droplet core	1,500-3,000	200			5,000-7,000
U Gaseous Core					
Open cycle	5,200	60-80		U plasma	
Vapor core	1,280	310		UF_4-HfC	6,000-8,000
Lite bulb	1,870				7,200
Electrothermal arc heating	400-2,000		H_2		5,773
Electrostatic ion	4,000-25,000		Cs		-
Magnetoplasma	3,000-15,000		H_2		-
U External Pulse Plasma Propulsion (EPPP)					
Fission	5,000-10,000		-	Fission plasma	
Fission/Fusion, Fusion	100,000			Fission/fusion, fusion plasmas	

Using the Δv values from Table 1 and the expression derived for propellant mass per initial mass of a rocked, we can calculate the percentage of initial mass that must be propellant to space missions to certain planets.

This data is plotted in Fig. 3 with specific impulses of 400, 800 and 1600 seconds chosen to represent chemical rockets, solid core nuclear rockets and gas core nuclear rockets, respectively.

It can be seen that increasing the specific impulse by using nuclear propulsion significantly reduces the percentage of total mass that must be allocated for the propellant, thereby increasing the payload. For long distance missions, increasing the I_s becomes increasingly important as the propellant mass approaches 100 percent of the total mass.

Other nuclear propulsion designs do not utilize the heat from the reactor core to heat the propellant. In Nuclear Electric Propulsion (NEP) designs, the energy from a fission reaction or a radioisotope decay is converted into electrical energy using thermoelectric conversion or thermionics.

The electricity generated can be used to power ion thrusters with a specific impulses theoretically limited only by the power and voltage supplied. Ion thrusters are limited by a low thrust to weight ratio and by the presence of ionized particles outside of the system, however, for operation in space, these limitations are not applicable and ion NEP is a practical means of propulsion.

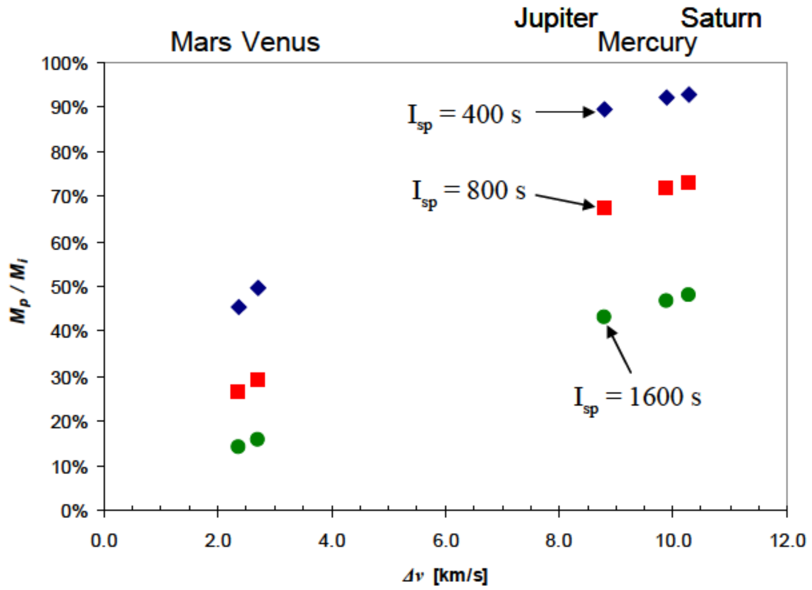

Figure 3. Propellant percentage of total mass vs. mission Δv.

5. SOLID CORE REACTOR CONCEPT

A typical solid core nuclear propulsion reactor can be divided into two subsystems. An example design of a solid core system is NASA's NERVA design shown in Fig. 4.

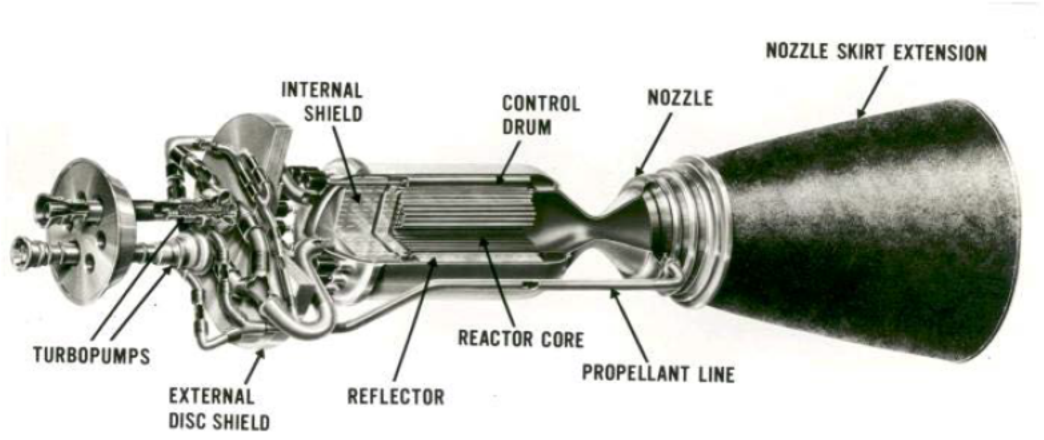

Figure 4. NERVA solid core nuclear propulsion system. Source: NASA.

The nuclear subsystem consists of the generation of heat from fission and controlling the reaction and heat. The nonnuclear subsystem controls the propellant flow as well as auxiliary power systems.

The solid core consists of a solid matrix which contains the fuel and is one of the limiting factors in core design. The core matrix must allow heat transfer to the propellant without reacting with the fuel and act as a moderator for the fission process. Typical core matrix materials are beryllium oxide (or other beryllium compounds), graphite, tungsten and its alloys, zirconium and niobium carbides. The propellant flows through the fuel containing matrix as shown in Fig. 5.

The heat produced by fission in the fuel heats the propellant which flows through the core to the rocket nozzle.

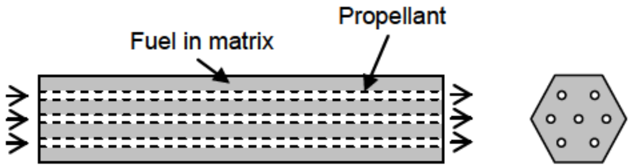

Figure 5. Example of fuel and propellant configuration for solid core nuclear propulsion system.

6. RADIATION SHIELDING CONSIDERATION

An important consideration for reactor design is protection from the radiation generated in the core. The spacecraft must be shielded from leakage radiation of both neutrons and gamma rays. The idealized model for attenuation of radiation intensity is the exponential attenuation law from a point source:

$$I(x) = I_0 \exp(-\mu_t x) \tag{7}$$

where μ_t is the material dependent attenuation coefficient (differs for neutrons or gamma radiation).

However, in these reactors, this equation must be modified for the conical geometry of the shields and to account for the radiation not acting as a point source. This modified attenuation equation is given as:

$$I(x) = I_0 GB \exp(-\mu_t x \sec(\theta)) \tag{8}$$

where G is a geometrical "view factor," B the buildup factor; a correction factor for a thick shield, and θ is the azimuthal angle from the centerline, and the secant reciprocal trigonometric function sec (θ) = 1 / cos(θ).

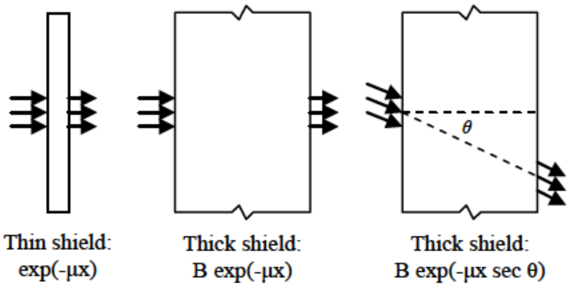

Figure 6. Schematic of radiation attenuation through different geometries.

Figure 6 is a schematic showing the physical differences between the geometries which result in the ideal exponential attenuation law and the modified equation.

For space operation, radiation from the reactor streams as a point source in vacuum. To protect the rest of the space craft from radiation a "shadow shield" must be used to block the direct line-of-sight between the reactor and the rest of the vehicle as shown in Fig. 7.

The shadow shield located near the reactor provides a cone of protection from the neutrons and gamma rays produced during fission. For nuclear reactors operated in air where radiation can be scattered around a shadow shield, a more comprehensive shield which encompasses the entire reactor must be used.

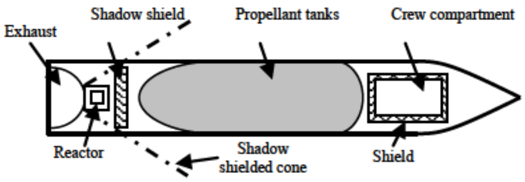

Figure 7. Shadow shield arrangement for nuclear rocket.

7. CONTROL SYSTEMS DESIGN

The amount of fissile fuel contained in the core is more than necessary to obtain criticality. This "excess fuel" makes control of the fission process extremely important for the safe operation of a nuclear propulsion system. Insertion of linear control elements cannot be used is space. Control drums around the core rotating in opposite directions and cancelling each other's angular momentum are considered instead.

For the initial start-up of the reactor the critical point is referred to as the clean-cold criticality. At the end of the "lifetime" of the reactor core, the criticality is referred to as hot. The amount of fuel required to maintain criticality at the end of the operation of the core is greater than that of in the clean-cold condition. Therefore, it is necessary to have excess fuel initially to enable criticality later in the lifetime of the reactor. The control system is designed to maintain criticality and is necessary for operation of a potentially supercritical device.

The reactivity and reactor period are two of the determining factors for controlling criticality. Reactivity is a parameter defining how the neutron flux changes with time. Reactivity is denoted ρ and defined in terms of the effective multiplication factor k_{eff} as [1]:

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \tag{9}$$

so at $\rho = 0$, $k_{eff} = 1$, there is no reactivity and the neutron flux is not varying with time.

Let the neutron population in a nuclear reactor at some t be n(t) and adopt a continuous population model. The effective multiplication factor can defined as the number of neutrons in a neutron generation after an average neutron lifetime relative to the number in the previous generation [1]:

$$k_{eff} = \frac{n(t) + dn(t)}{n(t)} \tag{10}$$

The change in the neutron population can be written as:

$$dn(t) = n(t)k_{eff} - n(t) = n(t)(k_{eff} - 1) \tag{11}$$

The rate of change in the neutron population would be:

$$\frac{dn(t)}{dt} = n(t)\frac{(k_{eff} - 1)}{\tau} \tag{12}$$

where τ is the average neutron lifetime between generations.

Separating the variables and integrating we get:

$$\begin{aligned} \int_{n_0}^{n(t)} \frac{dn(t)}{n(t)} &= \frac{(k_{eff} - 1)}{\tau} \int_0^t dt \\ \ln \frac{n(t)}{n_0} &= \frac{(k_{eff} - 1)}{\tau}.t \\ n(t) &= n_0 e^{\frac{(k_{eff} - 1)}{\tau} t} \end{aligned} \tag{13}$$

The neutron flux $\phi(t)$ and consequently the reactor power P(t) will rise with the reactor period T:

$$T = \frac{\tau}{k_{eff} - 1} \approx \frac{\tau}{\rho} \qquad (14)$$

according to the exponential growth equation:

$$\begin{aligned} \phi(t) &= \phi_0 e^{+\frac{t}{T}} \\ P(t) &= P_0 e^{+\frac{t}{T}} \end{aligned} \qquad (15)$$

Hypothetically, but not practically, the power in a reactor will rise on the basis of the prompt neutrons from fission quite rapidly in the absence rapid negative feedback or corrective action. For instance, for a graphite moderated reactor with $k_{eff} = 1.001$ or a 0.1 percent excess reactivity, a period of 1 sec, the power increase in 5 seconds would be by a factor of:

$$\frac{P(t)}{P_0} = e^{+\frac{5}{1}} = 148.4$$

For an enriched uranium light water moderated reactor, the prompt neutron period would be hypothetically shorter around 0.1 sec resulting in an increase in power of:

$$\frac{P(t)}{P_0} = e^{+\frac{5}{0\ 1}} = e^{+50} = 5.2.x10^{21}$$

Reactors do not just respond to prompt neutrons, since practically the delayed neutrons also affect the response of the reactor. The effect of the existence of delayed neutrons is an increase in the reactor period. The mean lifetime is increased from τ to the value:

$$(1-\beta)\tau + \sum_{i=1}^{6} \beta_i \tau_i \qquad (16)$$

For U^{235}, this is equal to 0.1 sec, with a resulting period of T = 0.1 / 0.001 = 100 sec and the power increase ratio within 5 seconds is a minor more manageable:

$$\frac{P(t)}{P_0} = e^{+\frac{5}{100}} = 1.05 \cdot$$

Practically then, he reactor response is so slower due to the presence of delayed neutrons, that enough time is available for corrective or negative feedback actions.

This provides a simple argument about the time behavior of a reactor. A more accurate representation is provided by the solution of the one group diffusion equation in the time dependent situation.

Control drums for space reactors are situated around the core in the reflector. The control drums are composed of several different materials which allow for the control of the reactivity of the reactor. In Fig. 8, a conceptual example of a control drum is shown. In this example, the drum contains three materials, beryllium, europium oxide, and gadolinium oxide. Beryllium is a good neutron reflector and is used to operate the core at maximum power. Europium oxide is a good thermal neutron absorber and acts to slow the fission chain reaction. Gadolinium oxide is an even more efficient neutron absorber and has strong absorption cross-section resonant peaks.

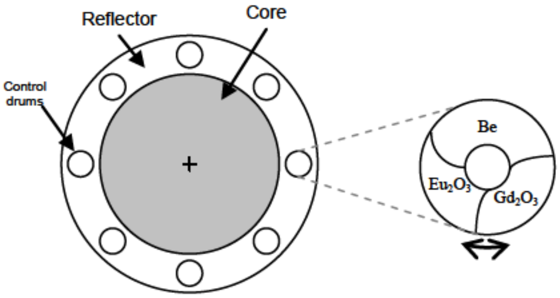

Figure 8. Schematic of control drum configuration.

To control the fission process, the control drums can be rotated so that a more reflecting or more absorptive material is facing the core. In this example, for maximum operation, the highly reflective beryllium would be rotated to face the reactor. To shut down the reactor, the gadolinium oxide would face the reactor resulting in a subcritical core. Rotation of the drums provides precise control of the reactor's reactivity, thus allowing for control of criticality throughout the lifetime of the reactor.

8. GASEOUS CORE REACTOR DEVELOPMENT

In a solid core nuclear reactor, the temperature is limited by the melting temperature of the fuel and matrix materials. In a gas core reactor, the fissile fuel would be in gaseous form which allows the temperature of the core up to 10,000 K. The gaseous core would be surrounded by a moderator material and a reflector. This high temperature combined with the advantage of using a pure hydrogen propellant could achieve very high specific impulse values [5].

There are a number of issues with the design of a gas core reactor. To sustain criticality, the core must be maintained at approximately 25 psi.

This results in exhaust products containing radioactive fission products and unburnrd fuel. Not only is this an issue because of the release of radioactive material, the fuel is exhausted before being fully utilized increasing the amount of expensive fuel required for a rocket.

To overcome the separation of fuel from the exhaust, a system using strong magnetic fields to contain the gaseous fuel is proposed.

A conceptual design of a gas core nuclear propulsion system is shown in Fig. 9. The magnetic field creates a toroidal shape plasma through which the propellant can be passed through, since the fuel is highly ionized while the propellant is only partially ionized. The propellant flows around the outside of the core acting as a coolant before entering the core and being exhausted. Fission control can be accomplished using control drums similar to those used for a solid core reactor.

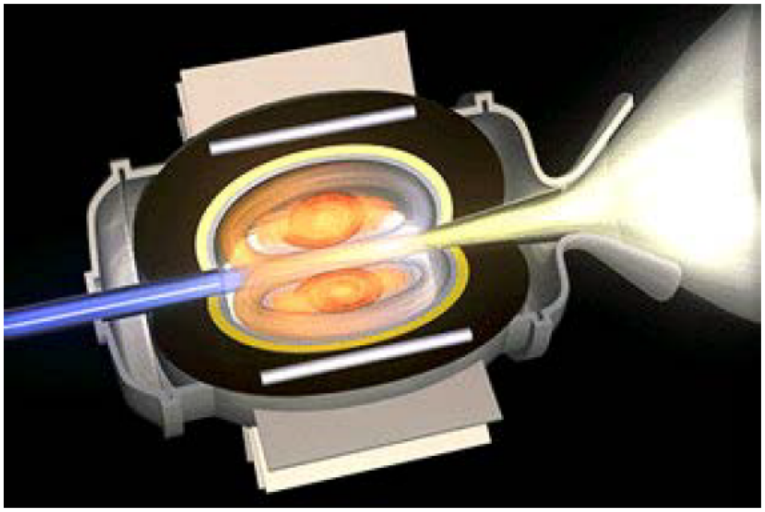

Figure 9. Conceptual design of gas core nuclear propulsion system. Source: Los Alamos National Laboratory, LANL.

9. ION THRUSTER PROPULSION DEVELOPMENT

A nuclear reactor produces a large amount of energy per unit mass of fuel consumed, however, the temperatures generated by a solid core reactor are limited by the fuel and moderator materials' melting temperatures, which limits the exhaust temperature and the specific impulse produced. One method of generating propulsion using fission is to convert the thermal energy into electrical energy which can be used to accelerate the propellant using electrostatic or electromagnetic forces [4, 6].

Energy can be converted from heat to electrical energy by thermionic emission. When a hot metallic plate is separated by a short distance from a cold metallic plate, the temperature difference drives an electric current. A schematic of thermionic conversion is shown in Fig. 10.

Once the energy from fission has been converted into electrical energy, this energy can be used to ionize the propellant and accelerate the rocket. Lithium and cesium are desirable propellants because of their low ionization energies and low atomic weight. Ion thrusters accelerate ions by applying a strong electric field in which the electric field applies a force on the ions proportional to the field strength. The exhaust velocity of an ion exiting an ion thruster is given by:

$$v_e = \sqrt{\frac{2Ze}{m}\Delta V} \tag{17}$$

where Z is the number of electrons removed from the ion, e is the electronic charge, m is the ion mass and ΔV is the voltage drop across the accelerator.

Recalling that the specific impulse is proportional to the exhaust velocity, it can be seen that for ion thrusters I_s is limited only by how much voltage can be applied. It should be noted that the thrust produced by ion accelerators is less than conventional chemical rockets; however, ion accelerators have the potential to be extremely efficient in fuel and propellant consumption.

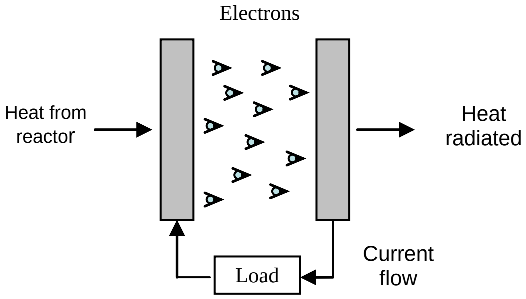

Figure 10. Schematic of thermionic conversion of thermal to electrical energy.

10. DISCUSSION

The importance of the need of high specific impulse I_s designs on the rocket performance is analyzed and the benefits of nuclear reactors over chemical rockets are explored. Some details of the designs of solid core nuclear reactors for propulsion were studied including the core design, shielding and fission control drums.

The true near term potential of nuclear propulsion is for a possible space mission to Mars. The higher specific impulse of the nuclear rocket can reduce the mission time for a Mars mission from about a year for a chemical rocket, to a few weeks in the case of a nuclear rocket. It also allows for a larger payload.

This may be crucial to avoid the effects of space radiation from solar flares on the astronauts, as well as avoiding the effects of gravity's absence on the muscular, bone, and other bodily functions in long duration space missions [1].

The most promising options for near future space solar system space exploration are identified as the newer technologies of nuclear powered ion thrusters and gas core nuclear reactors.

Nuclear power has made an undeniable impact on the world for power generation, medical applications and many other areas. Its utilization for space exploration as a means for propulsion is the next frontier for nuclear power to advance the state of technology. Harnessing the remarkable power of nuclear energy is an important step in the further exploration and understanding of space.

11. REFERENCES

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