Space Nuclear Thermal Propulsion Design

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INTRODUCTION

Space Nuclear thermal propulsion (NTP) systems utilize a nuclear reactor to heat up a liquid and propel the spacecraft forward. The idea of an NTP system goes back to the development of space travel itself, notably NASA's NERVA Project [1]. One of the main proponents for NTP systems over chemical rockets is its ability to cut the time of space travel down drastically. This is due to the fact that a nuclear rocket can generate much more energy on a per molecule basis than a chemical rocket. This essentially translates to Specific Impulse (I_{sp}) that describes the efficiency of fuel. A chemical rocket will reach an (I_{sp}) of 400-500 seconds, whereas a NTP rocket can reach values of 500-1000 seconds.

To this end, the main component of the NTP will be a High Temperature Gas Cooled Reactor (HTGR) to create the fusion to reach the (I_{sp}) values necessary for this mission. This type of reactor is especially useful because it creates an environment where the temperature will be higher than standard Light Water Reactors (LWRs). This is important because an increase in temperature causes a higher thermal efficiency and thus a higher thrust. Mechanical and Nuclear Engineering students at Virginia Commonwealth University are working with a faculty sponsor with the main objective to design a theoretical NTP system. The project will be focused on how a NTP system should work outside of a planet's gravitational pull, meaning that the scope would be for the interplanetary part of a trip between say Earth and Mars.

DESIGN OVERVIEW

For the space NTP design, a maximum power of 400 MWth and mass flow rate of the coolant, 25 kg/s, were established as two main design parameters. 400 MWth is a similar value to current modular gas-cooled reactors. Designs of NTP systems range in power though, from NERVA's 1137 MWth, the ANL-200 200 MWth, and MHTRG-350 350 MWth. The mass flow rate was chosen such that the maximum attainable velocity of the vehicle could be achieved. With these values, the specific impulse was estimated to be approximately 577 seconds, resulting in a launch vehicle maximum attainable velocity of about 3670 m/s. A helium cooled HTGR is selected as the nuclear reactor for the NTP system. Helium (He) is most commonly used for gas-cooled reactors; He is also inert. The estimated average fuel temperature will be of 4000 K and the average coolant temperature of 2023 K. The initial Reynolds number exiting the nozzle was found to be approx. 700,000, indicating an extremely turbulent flow pattern. The helium propellant will travel through the reactor core channels, heat up, and exit the nozzle to produce thrust.

The NASA NERVA Project shown in **Fig. 1** is used as a model example for the NTP design in this project. Generally speaking, using NTP for space exploration is an especially novel idea due to the fact that most NASA designs use chemical based propulsion. At the moment current space missions utilizing chemical based fuel take approximately 259 days to reach Mars. The change from chemical to nuclear thrust is thus an important milestone in the space industry because it will slash travel times and decrease mission costs which will be essential for future man based missions.

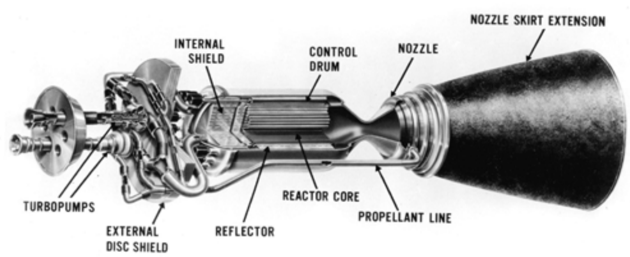

Figure 1. NASA NERVA Project Schematic [1].

Space reactors are quite different from conventional terrestrial nuclear reactors, designed for civil or military applications in terms of material selection, neutronics and thermal-hydraulics considerations. For the purpose of space missions, a specific HTGR needs to be designed and utilized in the NTP project. HTGRs are the preferred type of reactor because of the high temperatures they can achieve, with outlet temperatures reaching upwards of 900 ºC to 1000 ºC [2]. These conditions are especially necessary for our desired purpose of reaching higher speeds than conventional chemical rockets.

Beside high outlet temperature, HTGRs are much safer to operate compared to LWRs. The HTGR utilizes a Tri-structural ISOtropic particle fuel kernel, or TRISO fuel. This type of fuel is characterized by its three layers of ceramic material [3]. These fuels are very small (about the size of a poppy seed) but very robust because of the coating. This fuel is much safer than conventional fuel because TRISO fuel is structurally more resistant to neutron radiation, corrosion, oxidation and high temperatures. The TRISO fuel is incapable of melting at the temperatures it will experience, avoiding the main issue faced in the disaster at Chernobyl. Additionally, each particle acts as its own containment system due to the three layers of protection, this allows for a greater retention of fusion products. The control rods located in the center of the core will be the startup control rods. The control rods throughout the core will be used primarily to adjust the power levels (if necessary) and to scram the reactor if an emergency occurs. Coolant channels, fuels channels, and other aspects of the fuel blocks to be used in the reactor core can be illustrated by **Fig. 2**, which served as a model design of the fuel bundle and configuration used in the HTGR.

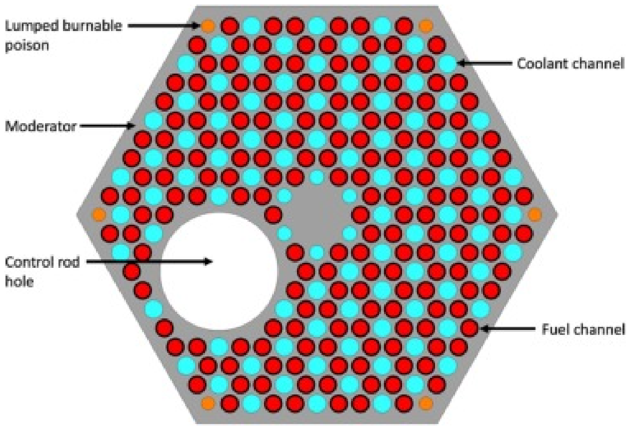

Figure 2. Cross-Section of a Single Fuel Block [3].

The NASA NERVA rocket was used as a basis for this design. The propellant travels through a pump around the nozzle, through the nuclear reactor core, and out the nozzle at a fast speed. Control nozzles are used to orient the vehicle 180 degrees during the reversal stage as well as course correction. **Fig. 3** shows the general schematic and flow of the propellant.

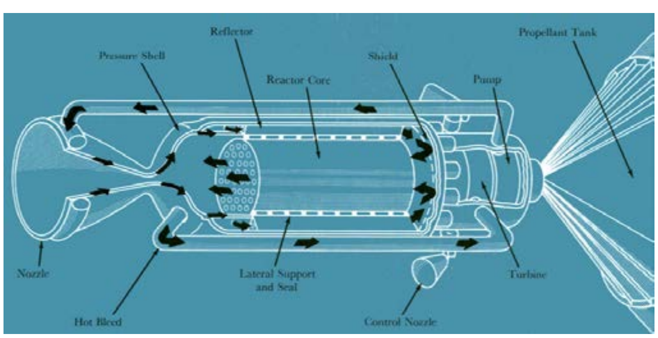

Figure 3. Shows the inside of the NERVA rocket [2].

The NTP system designed under this project differs from other NTP systems in a few key innovative aspects. This design will utilize a smaller, modular reactor. During launch and travel, weight and size are important factors, so limiting the size and mass of the reactor is indispensable. Modularity means that the reactor will be easier to transport and assemble. The second innovative point is the primary goal of the design is to achieve a higher specific impulse, faster speed of travel, with the aim of achieving better fuel economy (less fuel needed), which can be realized by iterating the geometry design of the reactor through modifying the HTGR reactor Serpent code or CFD analysis in ANSYS Fluent. Having a higher specific impulse and better usage of fuel would lead to this design being used more often. The last innovation of this design is on the selection of materials for the reactor. The most state-of-the-art innovative findings on fuel and moderator will be adopted in this design.

DESIGN METHODOLOGY

The book "Principles of Nuclear Rocket Propulsion" was examined in-depth to understand the fundamentals behind our intended design [2]. The VCU Libraries online search tool and multiple faculty in the VCU College of Engineering who specialized in Nuclear Engineering helped with bringing up the knowledge and direction necessary to create a feasible and cheap design.

The computer-aided design (CAD) of the nuclear thermal propulsion system will be created. The entire design should fit diameter-wise within a Falcon 9 fairing. Since we are planning to assemble the vehicle in space, we do not need to have height constraints. The helium tank volume has been calculated to be 104 cubic meters, based on the amount of helium needed. This will be translated to the dimensions of a cylindrical pressure vessel with spherical end-caps. Piping will need to be chosen based on the pressure, pressure head, length of total piping, etc. This ties into optimization methods provided in VCU's Thermal Systems Design course. The pressure can be derived from the mass flow rate established by the turbopump which is currently designed for 25 kg/s. Elbow fittings and other types of fittings will be examined for use of piping. For the CAD of the reactor core pressure vessel, it will most likely be cylindrical with a cone-shaped upper portion and lower portion, due to stresses of the helium along the walls of the vessel. These shear stresses must be minimized such that the mass is lightweight and curved or "lofted" surfaces from a smaller to a larger diameter do not increase shear stresses on the walls.

The reactor itself will need to be optimized and calculated for the number of boss-extrudes through the graphite, number of control rods, diameter of boss-extrudes (channels) and control rods, etc. The prismatic hexagonal fuel block's properties will need to be examined and potentially changed for our intended design purposes. Neutronics model and calculations can be performed with established computational codes such as the Monte-Carlo reactor code Serpent [4]. The team has been diligently working to utilize Serpent by getting access approvals, downloading the code manuals, and submitting the required information necessary to use the software. It is likely that Serpent may not be useful if our design cannot be optimized in the way we expected. And many other design problems need to be addressed at this moment such as how will we optimize the number of channels the propellant will travel through the graphite core? How will we optimize the diameter of those channels? For these questions, the Computational Fluid Dynamics (CFD) software will be used to estimate values and determine the best design of the nuclear reactor core. Software like ANSYS Fluent has the capabilities to import our future SolidWorks CAD, create a mesh of nodes, establish boundary conditions and fluid properties, and run simulations. This is one way we can optimize our CAD of our reactor core and it is channels.

Lastly, the nozzle dimensions will need to be found. Most propulsions systems are dealing with combustion; our design will not. Research will need to be done in order to see what the best dimensions of our nozzle design should be. Possible designs include a bell shape, a straight "loft" from the inner diameter to the outer diameter, and an inward curved "loft" from the inner diameter to the outer diameter. A nozzle is planned to be sourced per the specifications of our design, like mass flow rate and speed.

PRELIMINARY DESIGN RESULTS

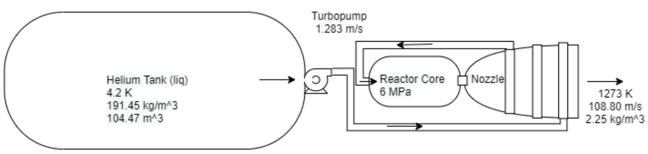

Figure 4. Propellant Flow Diagram.

For the simplest version of our design, **Fig. 4** shows how the propellant flows. The cryogenic liquid helium is pumped around the nozzle and through the reactor core, heats up, and exits the nozzle at an extremely fast velocity. The current design first pumps helium liquid at 4.2 K and 191.45 kg/m^3 from a tank of 104.47 m^3 through a turbopump at 25 kg/s through a series of pipes to wrap around the nozzle. This is done for effective heat transfer and regenerative velocity purposes. Next, the fluid will be piped into the reactor core and will heat up as it travels through the channels of the prismatic fuel blocks. After almost being superheated, the helium vapor will exit the nozzle at 1273 K, 2.25 kg/m^3, and 108.80 m/s. Boil-off is a concern for many liquid-fueled rockets. Since our design is planned to be assembled, fueled, and launched in space, this will not be of great concern.

Systems in the vehicle were researched and identified, per the purpose of the project, with each system having a certain mass. Our design will include a core (graphite, control rods, fuel elements), a primary propellant system for propulsion, a secondary propellant system, a battery system (uninterruptible power system) to power the turbopump, a nozzle to aim thrust, and a structural system frame to secure each system together. The secondary propellant system will be utilized for cooling the core from decay heat (approx. 12 MWth) during shut-off by circulating coolant through coating-covered cooling channels mounted to the outside of the vehicle to provide maximum heat transfer. In addition, a payload system will hold the payload in place. Vernier thrusters will control the pitch, roll, and yaw during interplanetary travel and orbit around Mars. These thrusters will also be used for orientating the vehicle such that it will slow down to reach the optimal orbiting velocity around Mars. Lastly, piping will connect the propellant tanks, core, and nozzle subsystems together.

Optimization will be further completed to improve the efficiency of the reactor channels and maximum velocity of the vehicle. Our manufacturing plan is to launch each component in sections such that each will fit in the volume of a Falcon 9 fairing and below the maximum launch mass of 8,300 kg. Some important values of the design are summarized in **Table 1**.

Table 1. Preliminary Design.

Parameter	**Value**	**Units**
Max Power	400	MWth
Mass Flow Rate	25	kg/s
Specific Impulse	576.64	seconds
Max Attainable Velocity	3671.40	m/s
Average Fuel Temp	2244.38	K
Average Moderator Temp	2040.76	K
Average Propellant Temp	2023.08	K
Re, at steady state, nozzle	699,847.15	-

In terms of the innovations and other major decisions utilized in the design, **Table 2** was created to show some of these aspects. One main innovation is the use of FCM (Fully Ceramic Microencapsulated) fuel pins with TRISO fuel inside each pin [3]. Further aspects like number of coolant channels, lump burnable poison material, etc. will be established and optimized.

Table 2. Innovations in Reactor.

Variable	**Chosen Type**
Particle Material	UO_2
Fuel Pin Type	FCM (Fully Ceramic Microencapsulated) Fuel
Fuel Type	TRISO Particles
Moderator	Graphite
Fuel Block	Hexagonal Prism w/ Cylindrical Coolant Channels

FUTURE WORK

Some of the main deliverables from theoretical studies of a NTP system being designed will be CAD drawings on the system as well as CFD, neutronics, and economic analysis of the system. This senior design capstone project may lay the groundwork for further designs of Nuclear Thermal Propulsion systems.

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