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AIR AND SPACE THERMAL ROCKET ENGINE WITH TURBOJET

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NTP (Nuclear Thermal Propulsion) relies on the high temperatures of nuclear fission to heat a propellant to produce thrust and can be applied to both jet and rocket engines. Both of these types of engines were explored by the United States during 1946-1973 with projects NERVA (Nuclear Engine for Rocket Vehicle Application) and NEPA (Nuclear Energy for the Propulsion of Aircraft); however, they had slow progress and the materials of that time were too heavy for aerospace vehicles. Today's materials allow for such technologies to succeed and a merging of the NEPA and NERVA designs has been made. This new hypothetical engine is called ASTRET (Air and Space Thermal Rocket Engine with Turbojet) for which Multiphysics modeling has shown that delivering a 70-ton payload into orbit by a single-stage spaceplane is not only possible, but cheaper than NASA's current SLS (Space Launch System) design or SpaceX's Falcon rocket. A spaceplane utilizing two ASTRET engines requires 2,000,000 liters of molecular hydrogen propellant with a heavy gaseous seed such as krypton. The added molecular weight of the seed allows for a fuel tank of a smaller volume, while keeping the mass of an otherwise larger tank with pure hydrogen the same. This reduces some of the challenges associated with manufacturing. The total weight of a spaceplane outfitted with 2 ASTRET engines is estimated to be 930 tons when fully loaded with propellant, payload, and fuel. The temperatures inside ASTRET have been kept at modest levels and are below the maximum ratings of the selected materials. Much more work must be done, including CFD modelling and verification of the general calculations, in order to declare that this engine has real world application.

I. INTRODUCTION

Access to space by a plane has been largely a concept of science fiction for over half a century. Many designs have been conceptualized with few technical details. To date, there has never been a truly reusable spaceplane that would be able to attain Earth orbit. Some noteworthy designs that have come close include: Space Shuttle, SR-71 Blackbird, X-15 Rocket Plane, and XB-70 Valkyrie. All of these designs had their own successes, with the latter having been originally conceived as a nuclear high-altitude plane. Out of all of these, only the Space Shuttle achieved Earth orbit, but at a cost of $450 million per launch and with only partial reusability[2].

The ASTRET engine functions as a jet engine during atmospheric flight and as a rocket engine above 25 km. The thermal power that is used to expand the working fluid (propellant) does not come from a combustible source, but from a nuclear reactor that relies on the fission of fissile nuclei (fuel). With an appropriate reactor configuration and choice of materials, a self-sustaining system may be achieved that stays within the temperature limits of the selected materials.

ASTRET is a thermal engine, which means that it does not need an oxidizer or any chemical reactions to occur in order to reach high temperatures. The propellant will be compressed and absorb heat from the reactor to reach operational stagnation temperatures and pressures before being expelled out of the nozzle. The common focus of creating a thermal rocket engine is to maximize the specific impulse. However, this is not practical, as the engine not only has to carry itself, but also its propellant and payload. This results in very large, impractical fuel tanks because the propellant which generates the highest specific impulse is molecular hydrogen. Hydrogen has very low density, which results in a high volumetric flow rate to produce a sufficient mass flow rate, leading to incredibly huge propellant tanks. NASA's study on the Nuclear Lightbulb engine involved seeding gaseous hydrogen with titanium vapor in order to better absorb energy from the reactor by lowering the specific heat of the mixture[4]. ASTRET's propellant will be molecular hydrogen seeded with 1% to 3% krypton. This allows the same amount of thrust for a longer period of time with smaller propellant tanks and lower specific heat capacity, at the cost of increasing the density and slightly lowering the specific impulse.

It is important to note that the numerical figures and any conclusions made in this study were based on undergraduate course materials. Further analysis and analytical research are required to prove the concepts, values, general operation, and conclusions made by the author.

II. ASTRET OPERATION

ASTRET uses all of the concepts from such projects as NEPA and NERVA. Some additional mechanisms have been conceptualized in order to have this engine switch between jet and rocket operations during flight, such as a clutch for the compressor and a variable nozzle inside the reactor. Aerospace grade 6 titanium Ti-5Al-2.5Sn is considered for the overall structure of this engine as this material can withstand elevated temperatures without losing much of its strength while also being light[5]. For applications where heat transfer between high temperature fluids is required, single crystal titanium carbide is a considered material due to its high thermal conductivity of 46 W/m·s[ref: 5]. The reactor and rocket nozzle may hypothetically utilize high entropy alloys cooled by cryogenic fluids. High entropy alloys may contain high temperatures and pressures inside the reactor without sacrificing the structural integrity. The overall structure of ASTRET consists of a jet engine with the combustion chamber replaced by a NERVA rocket. The cross-section and components of the conceptual engine are shown in figure 1 and the components are listed in table I with their respective numbers.

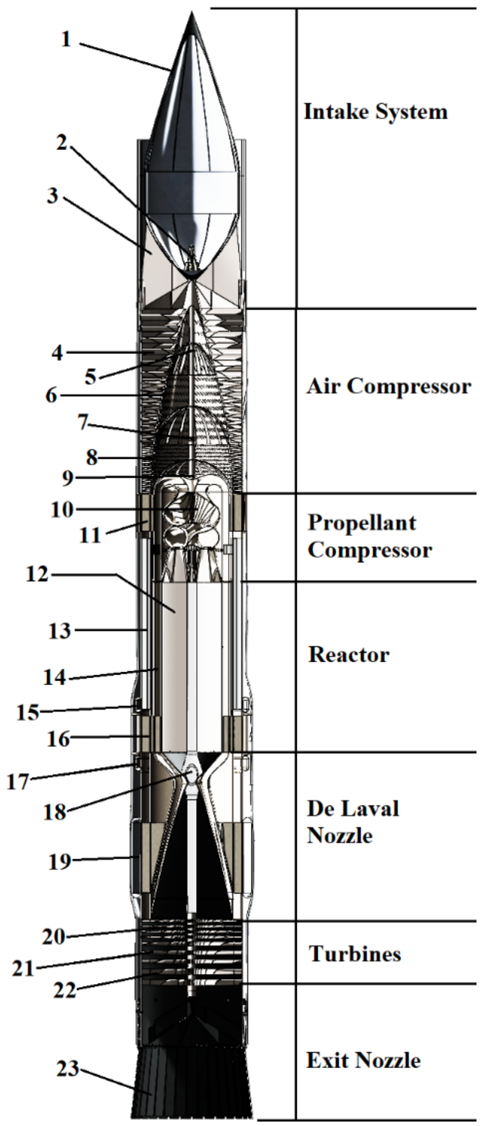

Fig. 1. ASTRET Components

II.A. Jet Operation

ASTRET's jet operation is like that of a jet engine, but the heat source is nuclear. The incoming air is heated by a closed nuclear cycle to minimize the radiation coming out of the exit nozzle (23) at lower altitudes. In addition to the heat source, ASTRET also utilizes a telescopic shock intake (3) to control the amount of incoming air into the air compressor through the shock cone (1). This extension has a unique position for three different flight velocities: subsonic, transonic, and supersonic. The intake air flow properties are calculated by normal and oblique shock relations.

TABLE I. ASTRET Component List

1	Shock Cone	13	Throat for Air Flow with 1,000 Heatsinks
2	Clutch Hydraulic Controls	14	Propellant Preheating Heatsinks
3	Telescopic Shock Intake	15	Pipe to Heatsinks
4	Compressor Stage 1	16	Hot Propellant Supply
5	Compressor Stage 1 Clutch	17	Pipe to Wing Turbine
6	Compressor Stage 2	18	Variable Throat Mechanism
7	Compressor Stage 2 Clutch	19	Propellant Supply
8	Compressor Stage 3	20	Turbine Stage 3
9	Compressor Stage 3 Clutch	21	Turbine Stage 2
10	Centrifugal 4:1 Compressor	22	Turbine Stage 3
11	Cooled Propellant Return	23	Variable Exit Nozzle
12	Reactor Core with 30,000 Fuel Rods		

In the subsonic regime, the telescopic shock intake is retracted completely to allow the maximum amount of air into the compressor. This compressor has three stages (4, 6, and 8), with a total compression ratio of 25:1. The incoming air is compressed and forced through 1000 heat sinks (13), which are kept at an average temperature of 2000 K by having the propellant function as the working fluid flowing through them. The air is heated by the heat sinks to the required stagnation temperature and is then allowed to expand through naturally occurring expansion fans into the turbines (20, 21, and 22). As the flow expands through the turbines, it increases its kinetic energy allowing it to still have a significant amount of energy when it exits the variable nozzle (23) to provide thrust. The amount of thrust is directly proportional to the intake pressure.

During the transonic regime, the shock cone creates an oblique shock and slows the flow down to below Mach 1. The telescopic shock intake extends to the shock in order to collect the heated and pressurized air. As the spaceplane increases its altitude further, the pressure and thrust drop while the velocity increases. When the velocity reaches Mach 2, the supersonic flow regime begins.

In the supersonic flow regime, the shock cone induces a secondary normal shock between it and the telescopic shock intake. Due to the velocity of the spaceplane, the oblique shock angle is decreased and the telescopic shock intake is partially retracted. This secondary normal shock guarantees the flow entering the compressor to be subsonic. All of this increases the pressure and temperature of the air to allow the engine to function at higher altitudes and velocities without using onboard propellant until an altitude of 25 km. At this point, ASTRET is ready to switch into rocket operation.

II.B. Rocket Operation

ASTRET's rocket operation involves onboard propellant to be heated by a direct nuclear cycle. This involves the propellant to be heated directly by the fuel rods in the reactor core (12) in order to maximize the heat transfer. Before the rocket operation begins, two things happen: the propellant flow is allowed to enter the De Laval Nozzle by activating the variable throat mechanism (18), and the compressor stages are disconnected from the turbine stages by clutches (5, 7, and 9) operated by clutch hydraulic controls (2). The propellant inside the fuel tanks is kept at liquid temperature, with the molecular hydrogen and seed having their own respective tanks in order to allow variation in the amount of the seed (krypton or xenon) in the propellant, as well as to maintain the correct temperatures for both fluids. A study is planned to analyze the effects and challenges of seeding the propellant more thoroughly.

The flow begins with liquid molecular hydrogen and liquid seed being heated to their gaseous temperatures, followed by mixing and forming the propellant. The propellant proceeds to enter the pump inside the spaceplane fuselage and is pressurized to 16 atm. Afterward, it enters the engine through the supply pipe (19) and cools the high entropy alloy material encasing the nozzle and reactor. Outside of the reactor, there are 15 concentric circular hollow heatsinks (14) through which heated propellant from the reactor enters. This heated propellant increases the heat transfer to the cold propellant and thus maximizes the heat transfer efficiency of the engine.

The propellant from the heatsinks (14) joins the now preheated propellant in the same flow and enters the 4:1 centrifugal compressor (10) at a temperature of 1100 K. The propellant is compressed further to 65 atm, and by isentropic relations, this raises the propellant's temperature to 1600 K. After flowing through the reactor, the propellant reaches a maximum stagnation temperature of 2600 K. In comparison to the NERVA stagnation temperature value of 3000 K, these values are modest.

Upon exiting the reactor, the propellant enters the De Laval nozzle where it rapidly expands and accelerates to Mach 4.5. The propellant continues expanding and driving the turbines until it reaches the variable nozzle, where it achieves a maximum exit Mach number of 6 and a constant thrust of 3.5 MN. Here, it should be noted that a thorough analysis of both propellant and air flow through the turbines is needed to learn how these flows will behave while expanding and driving the turbines.

III. THE REACTOR

III.A. Reactor Operation

The reactor has three modes of operation: jet, rocket, and standby. In jet operation, the reactor starts at 70% of its maximum power and uses the propellant as the moderator and working fluid flowing through the heatsinks (13) to heat the flowing air, as shown in Figure 2.

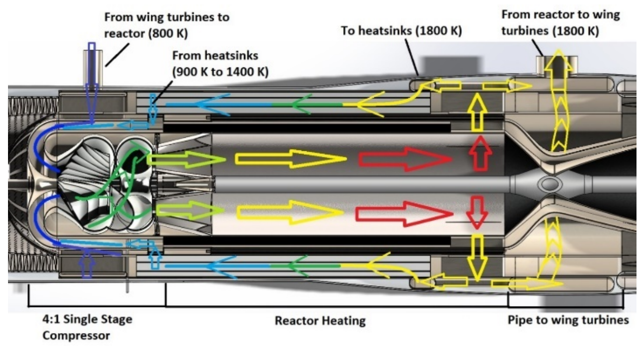

Fig. 2. Reactor Fluid Flow During Aerial Flight

The propellant follows through a closed cycle, which starts by exiting the centrifugal compressor and entering the reactor for heating. The temperature and mass flow rate of the propellant vary by altitude in order to maintain the proper temperature distribution inside the reactor. After the propellant has been heated to 2600 K, it decompresses by a factor of 4 and enters the pipes to the heatsinks (13) and wing turbines at a temperature of 1800 K.

The reactor, during the transition to rocket operation between 25 km and 50 km, allows the propellant to flow through the propellant heating heatsinks (14) in addition to the flow seen in Figure 2. The variable throat is gradually opened to allow the propellant to produce thrust, and new propellant enters the system through the main propellant pipe (19). Part of the heated propellant inside the reactor is routed out to the propellant preheating heatsinks (14), air heating heatsinks (13), and wing turbines, with the decompression ratio of 4. The amount of propellant flow to the wing turbines and air heating heatsinks may be adjusted and shut off during full rocket operation. The propellant that exits the propellant preheating heatsinks (14) mixes with the propellant being heated, the propellant coming from the air heating heatsinks (13), and the return propellant from the wing turbine. This mixed flow enters the centrifugal compressor and is heated with the majority of the mass flow exiting through the De Laval nozzle.

During standby operation, when ASTRET does not produce thrust, propellant still flows through the reactor and into the wing turbines thus cooling the reactor while producing electricity for the rest of the spaceplane. When the spacecraft docks with another vehicle, space station, or external fuel tank, the reactor may be shut off to save fuel and restarted before returning to flight. During the restart process, the standby operation may be engaged to cool the reactor once more. Further analysis is needed to determine the type of radiation shielding and a thorough analysis of the overall fluid flow.

A Multiphysics model was created to develop and test the ASTRET engine by using MATLAB code and Kerbal Space Program. This model's block diagram is shown in figure 3. Air and propellant parameters were calculated during calculations according to the temperatures and pressures reached inside the reactor and engine in MATLAB. Once the obtained results from MATLAB were satisfactory, Kerbal Space Program was used to verify these results. If the results were unsatisfactory, the engine and reactor parameters were modified accordingly and the Multiphysics model was reinitialized.

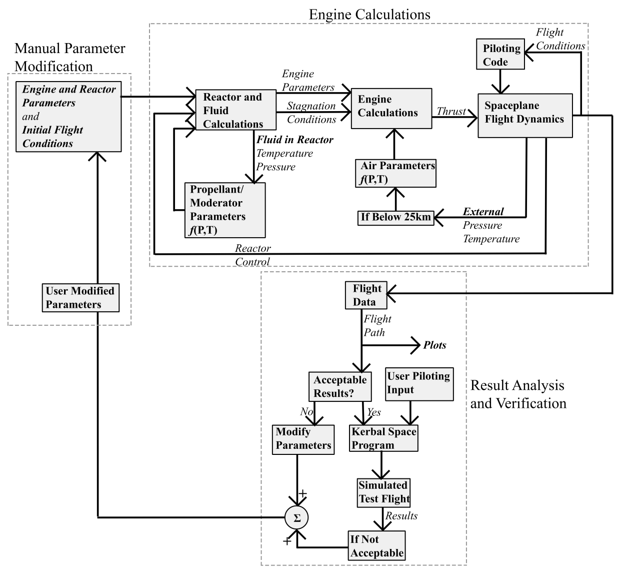

Fig. 3. Multiphysics Model Block Diagram

III.B. Open Cylindrical Reactor Equations

A unique aspect of ASTRET's reactor is its shape. Because it has rear turbines connecting to the front compressor stages, a shaft has to run in the middle of the reactor. This changes the neutron and thermal distributions of the core significantly, and was analyzed using a newly derived equation for the neutron flux, which has a direct effect on the temperature distribution. In order to account for the reflector, the perceived size of the reactor had to be scaled down a factor[3]. The Bessel function of the second kind is present in the equation, as the neutron flux is not evaluated in the center of the reactor. This equation was used to derive the bulk temperatures along the z-axis of the open cylinder for the propellant, cladding, and fuel. A radial thermal distribution was assumed through Bessel functions and the radial and axial thermal distributions were multiplied together to get the final thermal distribution result. The axial bulk temperature distribution may be found in nuclear engineering textbooks. The constants were solved through numerical methods, which accounted for the known thermal boundary conditions inside the core. The final results have been plotted in Figure 4.

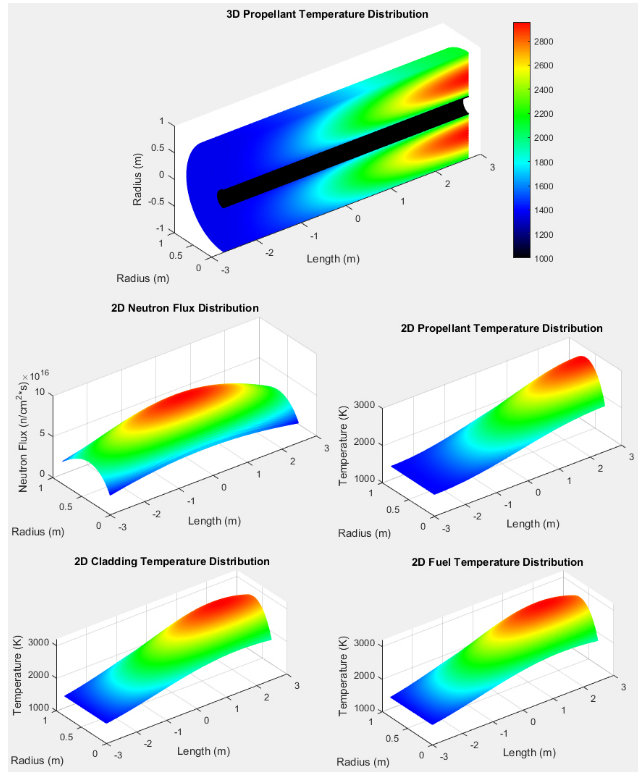

Fig. 4. Steady State Reactor Thermal Distribution

III.C. Reactor Materials

The reactor rod cladding and the fuel inside achieve an absolute maximum temperature of around 3050 K and 3150 K, respectively, which are within the range for the selected dispersed composite fuel form ($(U,Zr)C$). Table II displays the characteristics for NERVA/ROVER Program Fuel Forms[1]. The selected fuel has the highest thermal conductivity and one of the highest temperature ranges, which extends to 3500 K. The chosen ratios of uranium, zirconium, and carbon are 5.2%, 56%, and 38.8%, respectively, with a density of 5507 $\frac{\text{kg}}{\text{m}^3}$. At 20% enrichment of uranium, 15.6 tons of this fuel are enough for 150 flights to orbit and back before the reactor core has to be replaced.

Unlike the hexagonal fuel elements, the fuel rods in the ASTRET reactor resemble those found in a power plant, where the fuel is in the form of pellets inside a cladding. However, unlike a power plant fuel rod, the ASTRET fuel rods have a channel running down the middle of each. Therefore, the resulting fuel pellet will be in the shape of a cylindrical ring. The material chosen for the cladding was the industry standard zirconium carbide for its excellent thermal performance and thermal conductivity of 44 to 55 W/m·K within the 3000 to 3400 K range[2].

Some parts in the ASTRET engine are required to contain high temperatures under high pressures, while also being light. High entropy alloys (HEA) function within these constraints. Figure 5[ref: 6] features the yield strength as a function of temperature of HEAs and Inconel 718 for comparison. HEAs are a mixture of several different metals in near to equal amounts. These materials are not yet commercially available, but they show great promise for future development and utilization in aerospace applications.

TABLE II. Summary of NERVA/Rover Solid Core Nuclear Thermal Propulsion Fuels

	Coated Graphite Fuel Form	Carbide Fuel Form	Composite Fuel Form
Fuel Compound	UC2	(U,Zr)C	Dispersed (U,Zr)C
Matrix Material	Graphite	All Carbide	Graphite
Maximum Operating Temperature (K)	2750-3500	2800-3100	**2750-3500**
Thermal Conductivity (W/m · K)	25-50	8.2-10.0	**40-75**

IV. HIGH ENTROPY ALLOYS

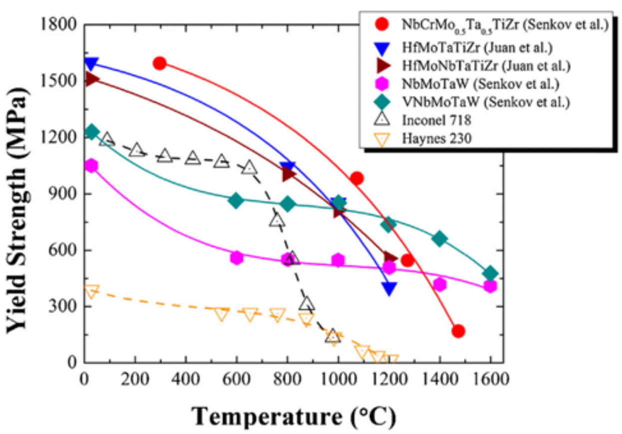

Fig. 5. Yield Strength Versus Temperature of High Entropy Alloys

Calculations were performed that determined the best HEA for the reactor shell is VNbMoTaW. According to Figure 5, this material has the highest yield strength at very high temperatures. Several different stress and strain analyses were performed, which guided the dimensions of the major parts yielding a net engine mass of 82.5 tons. Further studies with more sophisticated methods are needed in order to perform a thorough material analysis.

V. CONCLUSIONS

The design of a spaceplane engine that would utilize NERVA's a thermal rocket engine and NEPA's nuclear jet engine was created and Multiphysics modelling was used to test it. This engine's operation was described as a thermal engine that has no need for an oxidizer and is capable of flying in the atmosphere without combustion. Special equations for the open cylindrical reactor were derived. The reactor conditions were analyzed and it was determined that the best fuel was (U,Zr)C. A material analysis was performed, which determined that HEAs are the preferred material for high performance requirements.

It is very important to restate that the numerical values and conclusions made in this study were the result of undergraduate research. Much further analytical research at the graduate level is required in order to further assert, modify, and prove these results.

ACKNOWLEDGMENTS

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