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Nuclear Thermal Rocket: The Next Big Step in Space Exploration

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1. Introduction

In this review is discussed a little about the nuclear propulsion system, with historical perspective about the development of this technology. Low funding would not be a problem if wasn't the historical context, on which the competition for the space technology supremacy during the Cold War. In the present days it is not the case anymore, with the end of the political tensions, the exchange of knowledge is even more explicit with the advent of the Internet. Also modern computers and numerical routines in many areas of physics also provide cheaper and safer ways to develop this technology and provide the next step in space exploration.

2. Methodology

The rocket science was born with the new born century, the Russian scientist, Tsiolkovsky, father of the modern rocketry, published his paper, on which included the rocket equation.

$$\Delta v = \ln \left(\frac{m_f}{m_0} \right)^{-I_{sp} g_0} . \tag{1}$$

He idealized that Radium could provide higher propulsion efficiency and should be used for interstellar travels. With Eq. 1 is possible to obtain the final mass m_f of a projectile with initial mass m_0, for a given Δv in it's velocity, $g_0 = 9.81\ m/s^2$. The quantity I_{sp} is the specific impulse and is related with the exit velocity of the propellant by

$$I_{sp} = \frac{v_e}{g_0}. \tag{2}$$

It serves as measure for its efficiency. With the discovery of fission in 1938, with it a lot of interest in the atomic nucleus's high energy density by Einstein's [5] famous equation, when the 3-momentum is null, one obtains

$$\Delta E = \Delta m c^2 \tag{3}$$

Nowadays in nuclear engineering, Δm is called mass defect, ΔE the energy variation due the reduction of mass, and c is the speed of causality. The technology of fission, unfortunately, was specially developed in the Manhattan project during the World War II for the creation of atomic bombs.

It soon became evident that the use for fissile materials in space could provide a higher performance, however only for the theorists. The basic space technology was still inconceivable and advanced by the Operation Paperclip by the U.S. Government. The main advantage for aerospace propulsion systems is the high energy amount that it would be available to heat the propellant and increase is thermal energy, and convert it using a convergent-divergent nozzle, into kinetic energy via the equation bellow

$$v_e = \sqrt{\frac{2\gamma RT}{\gamma - 1} \cdot \left[1 - \left(\frac{p_e}{p}\right)^{\frac{\gamma-1}{\gamma}}\right]}. \tag{4}$$

Where P_e and P_0 are the pressure in the exit and in the beginning of the nozzle, γ is the adiabatic constant, R the specific gas constant and T the temperature.
Another development that would be necessary was develop the orbital maneuvers that would allow the transportation between planets, this started even in 1925 with Hohmann developing his transfer maneuver, basis for all others developed later.
This method is called patched conics approximation, in such a scheme, the analytically unsolvable 3-body problem is reduced to three 2-body problems and the spacecraft is out of the sphere of influence of the planets. The reason why it is called patched conics, the spacecraft execute a trajectory around the Sun and patches the sections of the two planet's light-cones, connecting the events of both orbital trajectories of departure and arrival and it is illustrated bellow.

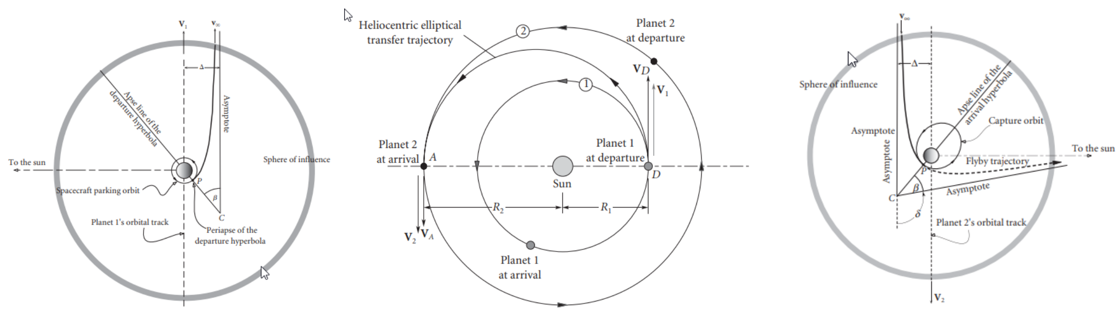

Figure 1: Analysis of the orbital maneuvers of departure and rendezvous in the orbital plane of motion at the instants of departure and arrival. Images from [1].

This method allows one to derive the change in velocity Δv_d necessary to make a spacecraft enter in the heliocentric path and the arrival's Δv_a to park in the destination planet. Those changes in velocities combined with Eq. 1 and Eq. 4 gives the mass ratio between the end and the beginning of the mission.v_{∞_d} and v_{∞_a} are the excess of hyperbolic velocity in departure and arrival respectively.

$$\Delta v_d = v_c \left(\sqrt{2 + \left(\frac{v_\infty}{v_c}\right)^2} - 1\right) \tag{5}$$

$$\Delta v_a = \sqrt{v_\infty^2 + \frac{2\mu_2}{r_p}} - \sqrt{\frac{\mu_2(1+e)}{r_p}} \tag{6}$$

Only in the late 50's, when American scientists developed the first thermionic propulsion system, and only in 1968 the Apollo 11 mission lead the firsts humans in the lunar soil, with Neil Armstrong being the first one. The history of NTR's as a high emergency technology basically ended, mostly because the major interest of the politicians in the Space Race was because of the propaganda.

3. Results and Discussion

As one can see, the development of the nuclear thermal technology was politically unstable. The exchange of knowledge was restrict between all countries, specially between the U.S. and the Soviet Union, the risk of important technical details could give great military/intelligence advantages about the state of the art of nuclear and space technology of each side.

When the United States won the Moon, basically the interest of politicians on space exploration felt drastically, the political agenda was about the image of the space technology supremacy.

Also, the experiments to optimize the technology was too high, and since there were no destination more distant than the Moon, the technological development of space science was directed to another way, which gave rise to the modern space systems of propulsion, telecommunication and the GPS.

Missions to another planet are made only by robots and satellites for scientific experiments and data collection, manned missions to Mars are currently impossible, specially by radiation effects on the human body , which Emrich [2] states that the human body can sustain healthy for only seven months in space.

In the present, the scenario for nuclear rockets may change drastically in the next few years specially because the possibility to send humans to colonize Mars. The public attention to space exploration is renewed, and even the human's hazard to the Earth's ecosystem, with catastrophic predictions by the scientific community about the actions of mankind.

Besides the eminent interest of citizens and natural catastrophes, the stable-peace in the political scenario of the space powers like United States, Russia, China, etc. makes possible the collaboration through the data sharing between scientists from all over the world, enhancing the capability to solve different problems.

Also modern numerical routines and discretization schemes can easily evaluate the reactors properties with high accuracy, exploring different possible outcomes based on different configurations of materials and geometries.

Much of the state of the art of nuclear thermal rocket science is focused on the study of the reactors by means in the increase in the exchange, LEU fuels, control drums for reactivity control and safaty modes for accidents. In example the EHTGR (Extremely High Temperature Reator), which can withstand maximum temperatures above 3000 K and average temperatures of 2900 K.

The FWT (fuel wafer thickness) in square lattices as showed above and also the MCC (moderator cooling channel) can greatly increase the total amount of heat exchanged.

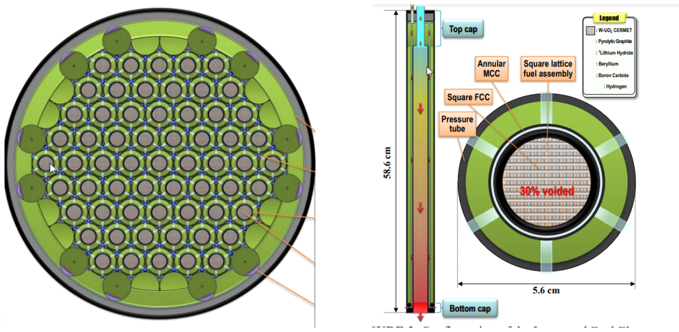

Figure 2: Cross sectional area of the LEU KANUTER EHTGR[3] also in HEU fuel version [4].

Control drums is the most conceivable control system in efficiency, time of response and dimensional positioning of the elements. The $W - UO_2$ Cermet has high melting point fuel and also prevents accidents due interactions of fuel.

4. Conclusions

Some of the history of the nuclear rockets is connected with the historical context of the World War II and Cold War, when the deadly nuclear weapons were conceived and a possible war was a daily possibility, makes the memories of nuclear physics scares for the major public, and is one of the first issues to tackle before the implementation in rockets.
The stable political scenario offers along modern methods of analysis the capability to view the problem from multiple point of views. With the cooperation of nations, more ingenious solutions for different problems offers the opportunity to take the next step on the space exploration

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