First year of Master's Internship
Report

Nuclear energy for space exploration: A technological necessity or a risky gamble for humanity and the wider environment ?

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Foreword

Let us first understand what this work constitutes.

For the past two months Victor, Yael, Yvon and I have studied, under the tutoring of Sarah and Julien. This work we have been doing differs from a "classical" internship in that it was mostly bibliographic until the end whence it differed.

Indeed, we had a mock-up debate wherein each of us students had to take on different roles and perspectives on our issue, which we will mention and study further down this report. This TER used to be a class centered around "Nuclear energy and Society", taught during the second semester of master's, its objective was to spur students into developing their ability to communicate and debate around a science-focused subject as well as to lead bibliographic research.

Our work differs from those that came before us in that we didn't focus or research on nuclear power plants or atomic weapon proliferation but rather on space exploration and radiation shielding.

We hope that you will find this report interesting and perhaps even learn a thing or two along the way.

Contents

Introduction **4**

1 Methods **5**
1.1 Nuclear Propulsion 5
1.1.1 Specific Impulse 5
1.1.2 Rocket Equation 6
1.1.3 Δv Budget 6
1.1.4 NTR 7
1.2 Shielding 7
1.2.1 Radiation in Space 7

2 Results **8**
2.1 Nuclear Propulsion 8
2.2 Shielding 8

3 Discussion **9**

Introduction

In this report we will study the following question :
"Nuclear energy for space exploration: A technological necessity or a risky gamble for humanity and the wider environment ?".

We will assume the role of Elon Musk, CEO of Space X a space technology company whose objective it will be to send a team of astronauts to the planet Mars and whose questionable ethics will lead us at the limit of what is considered acceptable in terms of radiation exposure, in opposition to NASA moto "as safe as possible" we would follow Elon's "move fast, break things". For this purpose we will study nuclear propulsion to show it is superior to classical means of propulsion on a trip to Mars, as well as radiation shielding and why it would be necessary for such a mission.

We will show that, assuming today's technology, it is quite unrealistic to propel a crew of four to Mars and back using anything else than a NTR and will try to show how nuclear energy and fissile materials can be used quite safely in the context of space propulsion. We will also show how much weight can be saved on shielding while still keeping the astronauts alive and healthy for the duration of the flight.

This report is heavily based on a 1997 book by Stephen J. Hoffman and David I. Kaplan at Johnson Space Center [2].

Chapter 1

Methods

1.1 Nuclear Propulsion

1.1.1 Specific Impulse

Specific impulse is a measure of how efficiently a reaction mass engine generates thrust.
It can be derived from the rocket thrust equation given by :

$$F = \dot{m}v_e + (p_e - p_0)A_e \tag{1.1}$$

Where p_e and p_0 are respectively the pressure of the exhaust and of the atmosphere, v_e is the speed of the exhaust, A_e is the area of the exhaust, $\dot{m}$ is the mass flow rate and F is the thrust.
From which can be defined the equivalent velocity:

$$V_{eq} = v_e + \frac{(p_e - p_0)A_e}{\dot{m}}$$

As well as the total impulse:

$$I = F\Delta t = \int F dt = \int \dot{m}v_e dt = mv_e$$

Which allows us to finally define the specific impulse:

$$I_{sp} = \frac{I}{mg_0} = \frac{v_e}{g_0} = \frac{F}{\dot{m}g_0} \tag{1.2}$$

Where g_0 is the gravity acceleration at sea level.

1.1.2 Rocket Equation

The Tsiolkovsky rocket equation also known as the ideal rocket equation defined as follows:

$$\Delta v = v_e \ln \frac{m_0}{m_f} = I_{sp} g_0 \ln \frac{m_0}{m_f} \tag{1.3}$$

With m_0 the initial mass of the rocket and m_f the final mass of the rocket. Given an effective exhaust velocity this equation allows us to find how much propellant mass is needed for a given change in velocity.

1.1.3 Δv Budget

The concept of Δv budget is an estimate of the total change of velocity required to perform each propulsive maneuver over the duration of a given mission this quantity can then be used as described in 1.1.2.

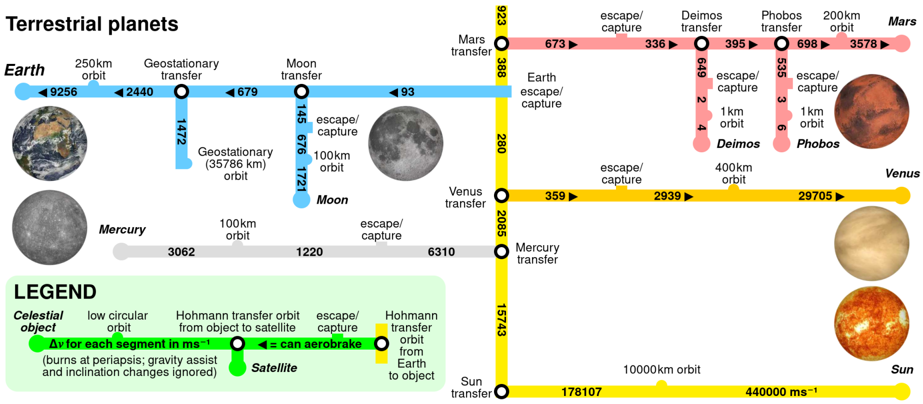

Figure 1.1: Delta-v map, assuming burns at periapsis, gravity assist, and ignoring inclination changes

For an Earth-Mars trip, a conservative estimate is located around $18000 m.s^{-1}$, it is important to note that even though we could save up on fuel by using more efficient transfer techniques this would also come at the expanse of travel time, which, we will see, becomes a major hurdle of space travel. On the other hand aerobreaking is an option both on Earth and Mars and should be fully utilized to save up on fuel.

1.1.4 NTR

Solid core nuclear thermal rockets, such as the NERVA-XE, make use of highly enriched U-235 fission reactor through which liquid hydrogen is passed serving as both coolant and propellant[1] as well as a good radiation shield. Liquid hydrogen is a propellant of choice due to its low molecular weight,

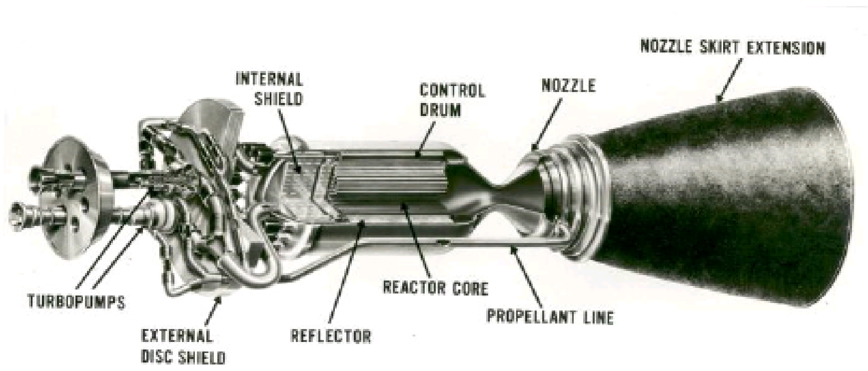

Figure 1.2: NERVA solid core nuclear propulsion system. Source: NASA.

which allows for high I_{sp} as well as its low neutron absorbing cross section. Solid core design operate at around 2000°C which in conjunction with the use of hydrogen yield specific impulses approaching 1000s. The design is limited by the containment chamber's wall melting. Some newer design, such as gas core NTRs could yield specific impulses around the 3000s mark. Inserer tableau Yvon

1.2 Shielding

1.2.1 Radiation in Space

Astronauts are exposed to higher doses of radiation in space mainly due to the lack of a magnetosphere and an atmosphere shielding them from SEP and GCR, the two main types of radiations in space. This effect grows stronger as you get further away from the earth as its magnetosphere grows weaker the further away one gets from it.

Chapter 2

Results

2.1 Nuclear Propulsion

2.2 Shielding

Chapter 3

Discussion

Acronyms

GCR: Galactic Cosmic Ray
SEP: Solar Event Particles
CEO: Chief Executive Officer
NTR: Nuclear Thermal Rocket

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[2] Stephen J Hoffman. *Human exploration of Mars: the reference mission of the NASA Mars exploration study team*, volume 6107. National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, 1997.