

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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Lastly, I thank you, reader of this report, for taking some of your time to understand and grade this work. Without you all of this would be useless.

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 on 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.

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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 [3].

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 :

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

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:

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

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:

$$\Delta v = v_e \ln \left(\frac{m_0}{m_f} \right) = I_{sp} g_0 \ln \left(\frac{m_p}{m_f} + 1 \right) \quad (1.3)$$

With m_0 the initial mass of the rocket, also known as wet mass, m_f the final mass, or dry mass, of the rocket, and m_p the mass of the propellant. 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.

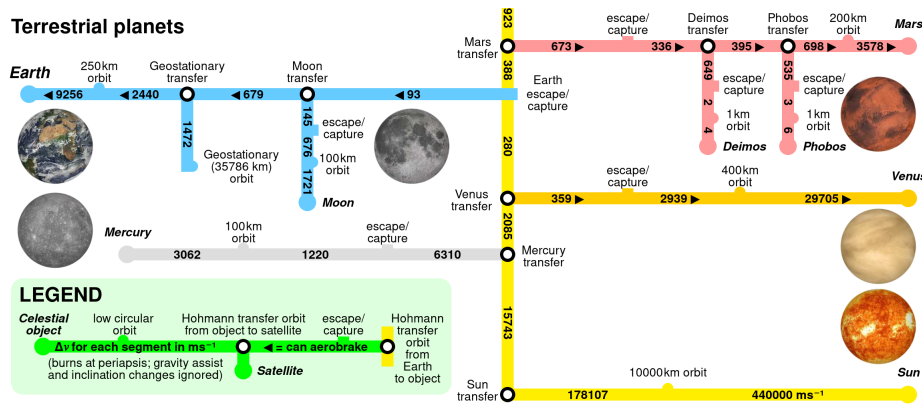


Figure 1.1: Delta-v map, assuming burns at periapsis, gravity assist, and ignoring inclination changes

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 expense of travel time, which, we will see, becomes a major hurdle of space travel. On the other hand aerobraking 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 [2] as well as a good radiation shield.

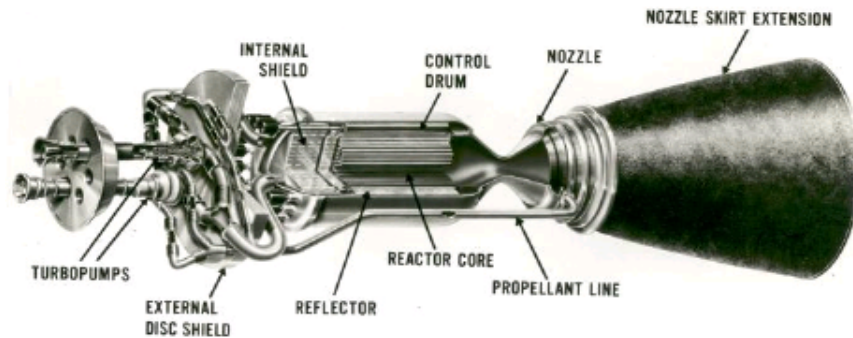


Figure 1.2: NERVA solid core nuclear propulsion system. Source: NASA.

1.2 Shielding

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. The dose grows stronger as one gets further away from the earth as its magnetosphere grows weaker the further away one gets from it.

The unprotected human body is quite weak to radiation, especially ionizing radiations and although the legislation is lacking for space workers the IAEA, specifies a dose of $20mSv$ per year averaged over five consecutive years (100 mSv in 5 years) and of $50mSv$ in any single year [1], for occupational workers. A quantity well under was is proposed by [3] as can be observed in figure 1.3.

	Mission	Duration ⁴ (days)	Dose (mGy) ¹			Dose equivalent (mSv) ^{1,2}			Effective dose (mSv) ³		
			0	20	40	0	20	40	0	20	40
Solar max.	Artemis II	10	1.5	2.1	2.5	10.2	6.9	5.9	6.3	5.1	5.3
	Artemis III	30	4.6	6.4	7.6	30.5	20.7	17.6	19.0	15.4	15.8
	Artemis III (surf)	23.5/6.5	4.2	5.8	6.9	27.7	18.7	16.0	17.4	14.1	14.4
	Gateway – 6 mo.	183	28	39	46	186	126	108	116	94	96
	Gateway – 12 mo.	365	56	78	92	372	252	215	232	188	192
	Mars DRM	621/40	99	137	163	644	440	377	405	331	339
	Mars DRM	840	128	178	213	855	580	494	533	432	442
Solar min.	Artemis II	10	4.6	5.2	5.6	28.5	15.0	12.2	14.6	10.9	10.7
	Artemis III	30	13.8	15.5	16.7	85.5	44.9	36.5	43.8	32.8	32.1
	Artemis III (surf)	23.5/6.5	12.6	14.0	15.0	77.1	40.5	33.0	39.8	29.9	29.2
	Gateway – 6 mo.	183	84	95	102	522	274	223	267	200	196
	Gateway – 12 mo.	365	168	189	203	1040	546	445	533	399	391
	Mars DRM	621/40	295	332	356	1795	950	779	929	702	688
	Mars DRM	840	386	434	466	2395	1256	1023	1228	918	899

¹Values have been calculated without the influence of any human tissue shielding and would be directly comparable to an area dosimeter placed at the center of the spherical shield.

²Dose equivalent is calculated using the ICRP 60 quality factor [ICRP 1991].

³Effective dose is calculated using the ICRP 60 quality factor [ICRP 1991] and ICRP 103 [ICRP 2007] tissue weights for a female astronaut [Slaba et al. 2010].

⁴X/Y format denotes X days in free space and Y days on the surface.

Figure 1.3: Mission Exposures derived by Scaling Daily Values from Figure 1.4 by Corresponding Mission Segment Durations, from [3]

	g/cm ² →	Dose (mGy) ¹			Dose equivalent (mSv) ^{1,2}			Effective dose (mSv) ³		
		0	20	40	0	20	40	0	20	40
Solar max.	Free space	0.15	0.21	0.25	1.02	0.69	0.59	0.63	0.51	0.53
	Lunar surf.	0.10	0.12	0.14	0.58	0.39	0.33	0.38	0.31	0.32
	Mars surf.	0.12	0.13	0.15	0.30	0.28	0.30	0.28	0.30	0.32
Solar min.	Free space	0.46	0.52	0.56	2.85	1.50	1.22	1.46	1.09	1.07
	Lunar surf.	0.27	0.28	0.30	1.56	0.82	0.67	0.84	0.64	0.62
	Mars surf.	0.25	0.26	0.28	0.61	0.55	0.56	0.54	0.56	0.59

¹Values have been calculated without the influence of any human tissue shielding and would be directly comparable to an area dosimeter placed at the center of the spherical shield.

²Dose equivalent is calculated using the ICRP 60 quality factor [ICRP 1991].

³Effective dose is calculated using the ICRP 60 quality factor [ICRP 1991] and ICRP 103 [ICRP 2007] tissue weights for a female astronaut [Slaba et al. 2010].

Figure 1.4: Daily Exposure within 0, 20, and 40 g/cm² Spherical Aluminum Shielding in Free Space and on Surface of Moon and Mars for Solar Minimum (2009) and Solar Maximum (2001) GCR Conditions, from [3]

1.2.1 Radiation in Space

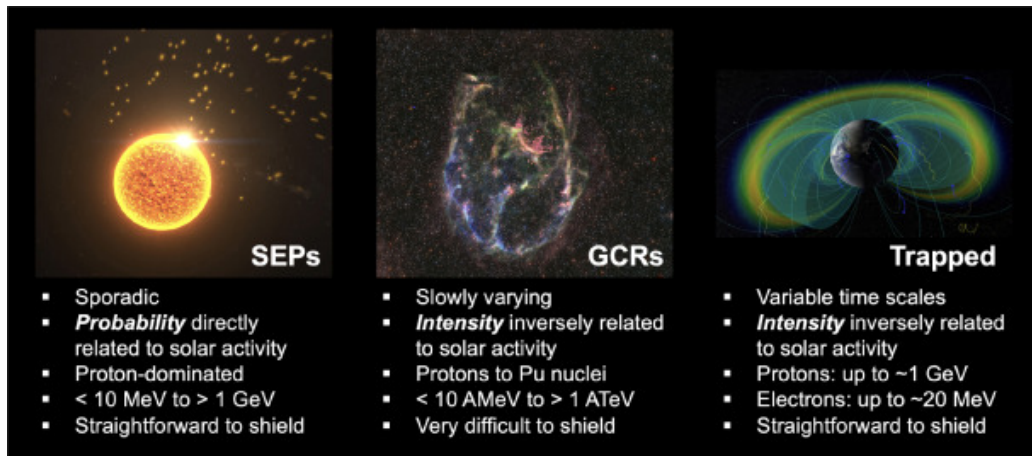


Figure 1.5: Major characteristics of SEPs, GCRs, and trapped particle radiation. Images courtesy of NASA Scientific Visualization Studio. SEP image credit: NASA's Goddard Space Flight Center Conceptual Image Lab, GCR image credit: NASA/STScI/CXC/SAO, processing by Judy Schmidt, CC BY-NC-SA, Trapped image credit: NASA's Scientific Visualization Studio.

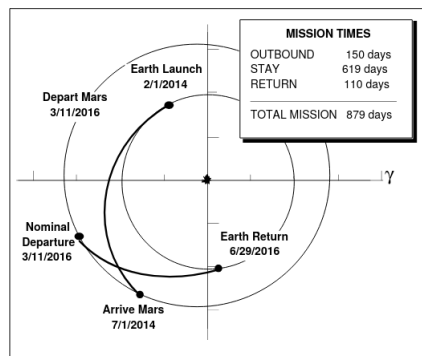


Figure 1.6: Typical fast-transit trajectory courtesy of [3]

In space, astronauts are exposed to three main kind of radiation environments, SEP, GCR and trapped radiations. For our purpose we will mainly focus on SEP and GCR radiations as the time spent around the earth and in the Van-Allen belt will be insignificant compared to the whole duration of the mission as highlighted in figure 1.6.

SEPs

SEP are high energy charged particles originating in the solar atmosphere and transported by solar winds. They are mostly composed of high energy protons as reported in [4]. Figure 1.7 shows the energy spectra from the 1989 solar event that resulted in a complete blackout of Hydro-Québec's power grid.

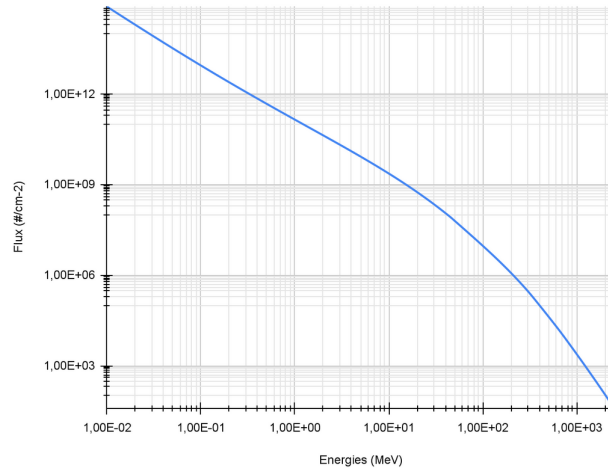


Figure 1.7: 9-13th of March 1989 Solar storm

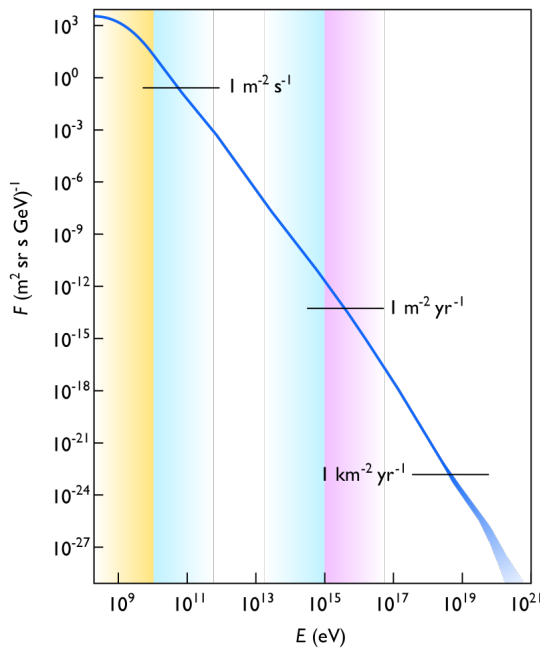


Figure 1.8: Cosmic flux versus particle energy at the top of Earth's atmosphere [5]

GCRs

GCR are high energy particles mostly composed of protons and HZE ions, some of them come from our sun but from our galaxy and other galaxies as well. The bulk of the flux is deflected to space by the heliosphere. Therefore, the solar cycle and thus the strength of the sun's magnetic sphere has a major influence on the influx of GCRs. Solar maximums and minimums, the time where the sun's activity is respectively at its maximum and its minimum will play a big role in how we deal with GCRs.

Chapter 2

Results

2.1 Nuclear Propulsion

2.2 Shielding

Chapter 3

Discussion

Acronyms

GCR: Galactic Cosmic Ray

CEO: Chief Executive Officer

HZE: The abbreviation comes from high (H), atomic number (Z), and energy (E).

IAEA: International Atomic Energy Agency

NTR: Nuclear Thermal Rocket

SEP: Solar Event Particles

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