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 ?

Submitted by

S. Bourgeois
Master of Fundamental Physics and Applications

Under the guidance of

S. Porteboeuf-Houssais, J. Donini
Profs.

Department of Physics and Engineering
University of Clermont Auvergne
4 Avenue Blaise Pascal
63178 Aubière

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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 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

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 (Hoffman, 1997).

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:

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

Where 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.

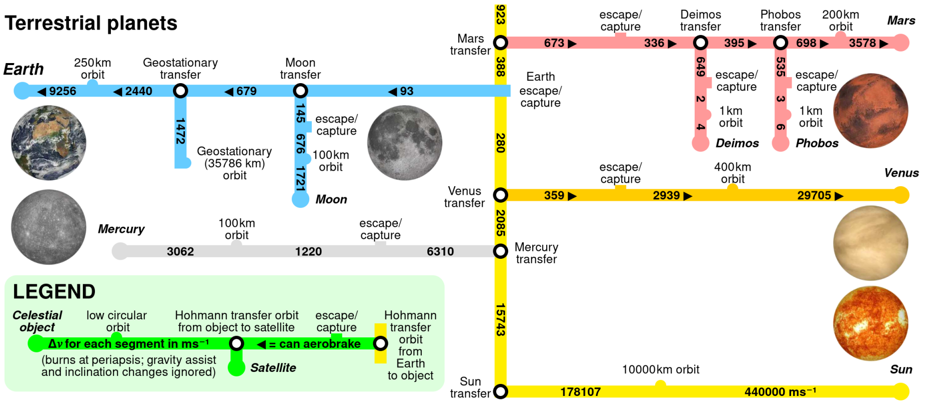

Figure 1.1: Delta-v map, assuming burns at periapsis, gravity assist, and ignoring inclination changes

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 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 (Finseth, 1991) as well as a good radiation shield.

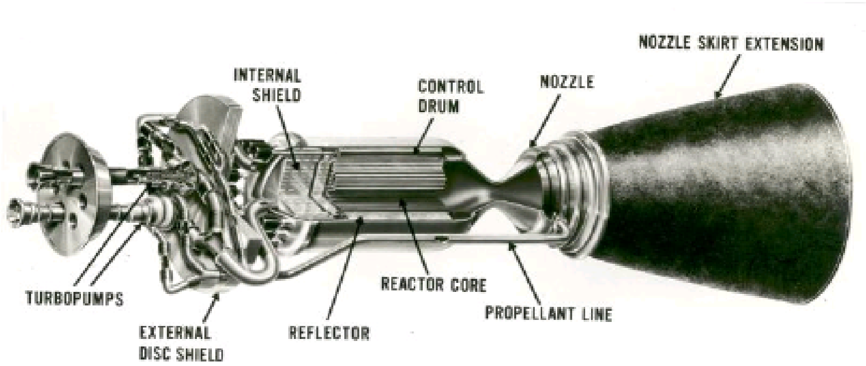

Figure 1.2: NERVA solid core nuclear propulsion system. Source: NASA.

1.2 Radiations in Space

1.2.1 Shielding

Astronauts are exposed to higher doses of radiation in interplanetary space mainly due to the lack of a magnetosphere and an atmosphere shielding them from SEP and GCR, the two main types of radiations they would be exposed to for an inter-planetary journey such as one from Earth to Mars.
The dose grows stronger as one gets further away from the Earth as its magnetosphere grows weaker and its atmosphere thinner the further away one gets from it. As for Mars, who lacks a strong magnetosphere such as Earth's, it does have a CO2 atmosphere which shields it from space born radiations, though less than Earth's thicker atmosphere.
The unprotected human body is quite vulnerable to radiation, long term exposure and accumulation of radiations can lead to sever health effects (Baumstark-Khan and Facius, 2002).

Although the legislation is lacking for space the IAEA, the UN legislative body, specifies a dose of $20mSv$ per year averaged over five consecutive years (100 mSv in 5 years) and of $50mSv$ in any single year for occupational workers (IAEA, 2018). A quantity well under was is proposed by (Hoffman, 1997) as can be observed in figure 1.4.

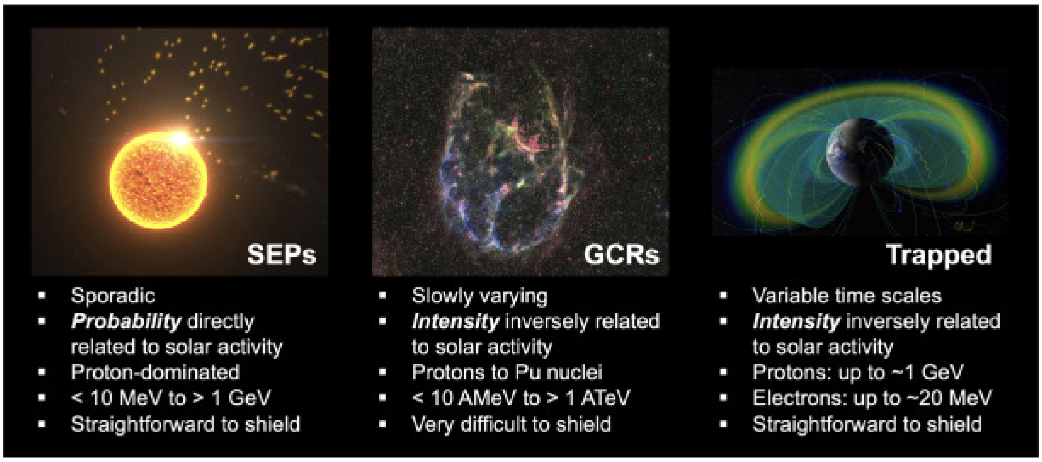

Figure 1.3: Major characteristics of SEPs, GCRs, and trapped particle radiation. Images courtesy of NASA Scientific Visualization Studio. SEP image credit: NASA's Goddard Space Flight Center Conceptual Image Lab, GCR image credit: NASA/STScI/CXC/SAO, processing by Judy Schmidt, CC BY-NC-SA, Trapped image credit: NASA's Scientific Visualization Studio.

The mean energy loss (stopping power) for a fast charged particle with speed v, charge z, and energy E, traveling a distance x into a target of electron number density n and mean excitation energy I, the relativistic version of the formula reads, in SI units is (Groom and Klein, 2000) :

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \left[\ln\left(\frac{2m_e c^2\beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right] \tag{1.4}$$

Where:
- m_e the electron resting mass
- c the speed of light in vacuum
- e the electron charge
- ϵ_0 the vacuum permittivity
- $\beta = \frac{v}{c}$
- $n = \frac{N_a \cdot Z \cdot \rho}{A \cdot M_u}$

This report will make use of NIST's tool, PSTAR (NIST).
With a default option, PSTAR generate the stopping powers and ranges for protons tabulated in ICRU Report 49 (Deasy, 1994) for 74 materials at a standard grid of 133 kinetic energies between 1 keV and 10 GeV for protons.

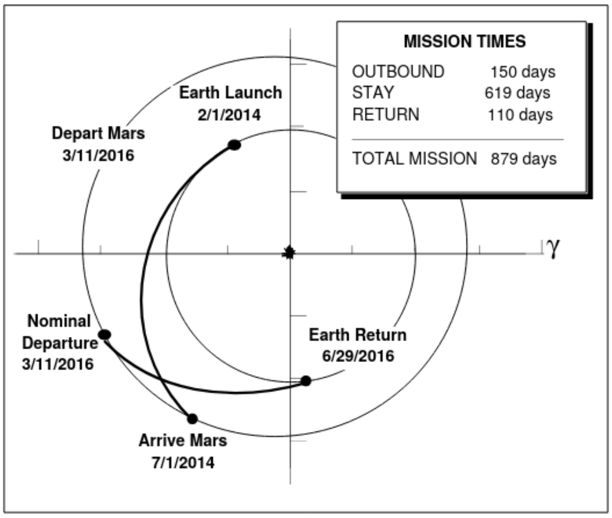

Figure 1.4: Typical fast-transit trajectory courtesy of (Hoffman, 1997)

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 4.1.

1.2.2 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 (Jiggens et al., 2019). Figure 1.5 shows the energy spectra from the 1989 solar event that resulted in a complete blackout of Hydro-Québec's power grid.

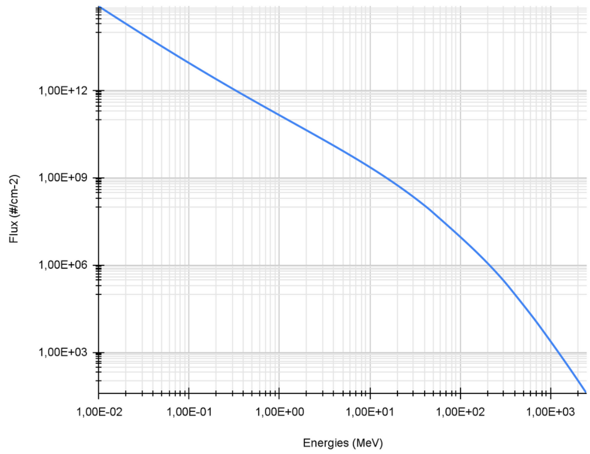

Figure 1.5: The energy spectrum of the 9-13th of march 1989 solar storm

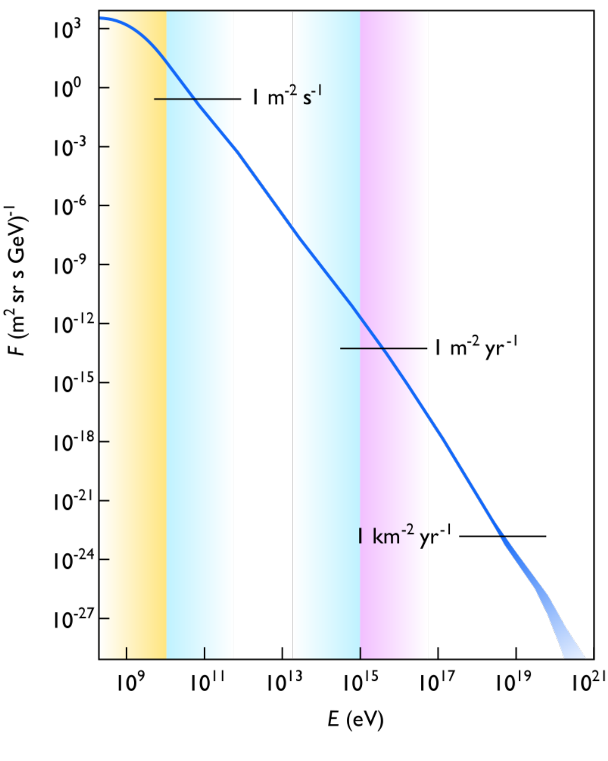

Figure 1.6: Cosmic Flux Versus Particle Energy At The Top Of Earth's Atmosphere (Sharma et al., 2008)

1.2.3 GCRs

CGR 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. Therefor, 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.

1.2.4 Dosimetry

Absorbed Dose

Absorbed dose is a dose quantity which represents the specific energy (energy per unit mass) deposited by ionizing radiation in living matter.

$$\bar{D_T} = \frac{\int_T D(x,y,z)\rho(x,y,z)dV}{\int_T \rho(x,y,z)dV} \quad (Gy) \tag{1.5}$$

Where:
- $\bar{D_T}$ is the mass-averaged absorbed dose of the entire item T
- T is the item of interest
- $D(x,y,z)$ is the absorbed dose density (absorbed dose per unit volume) as a function of location
- $\rho(x,y,z)$ is the density (mass per unit volume) as a function of location
- V is volume

Equivalent Dose

Equivalent dose is a dose quantity representing the stochastic health effects of low levels of ionizing radiation on the human body which represents the probability of radiation-induced cancer and genetic damage.

$$H_T = \sum_R W_R \cdot D_{T,R} \quad (Sv) \tag{1.6}$$

Where:
- W_R is the radiation weighting factor defined by regulation (ICRP, 2007). See Figure 4.3 for the values of W_R.

Effective Dose

Effective dose is a dose quantity in the International Commission on Radiological Protection (ICRP) system of radiological protection. It is a good measure of the health risks associated with radiations (on Radiological Protection, 2007).

$$E = \sum_T W_T \cdot H_T = \sum_T W_T \sum_R W_R \cdot \frac{\displaystyle\int_T D_R(x,y,z)\rho(x,y,z)dV}{\displaystyle\int_T \rho(x,y,z)dV} \tag{1.7}$$

Where:
- W_R is the radiation weighting factor defined by regulation. See Figure 4.4.

Chapter 2

Results

2.1 Propulsion

2.1.1 Nuclear Propulsion

Here we compare the difference in the fuel to dry mass ratio when using different technologies using Eq 1.3 and taking a Δv of 5543 m.s-1, accounting for the use of the nuclear engine as the transfer engine, ie. the rocket would be sent to space and would land using chemical engines and the NTR would only be fired from LEO to LMO.

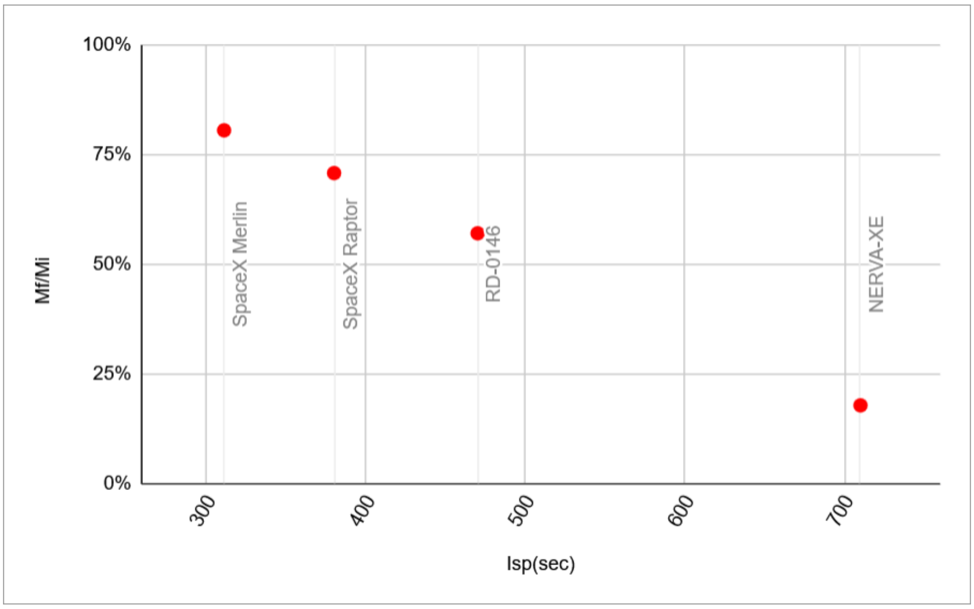

Figure 2.1: Ratio of fuel to dry mass relative to Isp for a typical Earth-Mars mission

Liquid hydrogen is a propellant of choice due to its low molecular weight, which allows for high I_{sp} as well as its low neutron absorbing cross section. Solid core NTR 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 in the 3000s.

2.2 Radiation in Space

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
LEO: Low Earth Orbit, between 160km and 2000km
LMO: Low Mars Orbit, similar to LEO
NIST: National Institute of Standards and Technology
NTR: Nuclear Thermal Rocket
SEP: Solar Energetic Particles

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Chapter 4

Appendix

	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

[1]Values 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.
[2]Dose equivalent is calculated using the ICRP 60 quality factor [ICRP 1991].
[3]Effective 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].
[4]X/Y format denotes X days in free space and Y days on the surface.

Figure 4.1: Mission exposures derived by scaling daily values from Figure 4.2 by corresponding mission segment duration, from (Hoffman, 1997)

		Dose (mGy)[1]			Dose equivalent (mSv)[1,2]			Effective dose (mSv)[3]		
	g/cm² →	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

[1]Values 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.
[2]Dose equivalent is calculated using the ICRP 60 quality factor [ICRP 1991].
[3]Effective 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 4.2: 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 (Hoffman, 1997)

Radiation	Energy	W_R
x-rays, gamma rays, beta particles, muons		1
neutrons	< 1 MeV	$2.5 + 18.2 \cdot e^{-[\ln(E)]^2/6}$
	1 - 50 MeV	$5.0 + 17.0 \cdot e^{-[\ln(2 \cdot E)]^2/6}$
	> 50 MeV	$2.5 + 3.25 \cdot e^{-[\ln(0.04 \cdot E)]^2/6}$
protons, charged pions		2
alpha particles, fission products, heavy nuclei		20

Figure 4.3: Radiation weighting factors W_R used to represent relative biological effectiveness according to ICRP report (ICRP, 2007)

Organs	Tissue weighting factors		
	ICRP26 1977	ICRP60 1990	ICRP103 2007
Gonads	0.25	0.20	0.08
Red Bone Marrow	0.12	0.12	0.12
Colon	–	0.12	0.12
Lung	0.12	0.12	0.12
Stomach	–	0.12	0.12
Breasts	0.15	0.05	0.12
Bladder	–	0.05	0.04
Liver	–	0.05	0.04
Oesophagus	–	0.05	0.04
Thyroid	0.03	0.05	0.04
Skin	–	0.01	0.01
Bone surface	0.03	0.01	0.01
Salivary glands	–	–	0.01
Brain	–	–	0.01
Remainder of body	0.30	0.05	0.12

Figure 4.4: Weighting factors (W_H) for different tissues