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ABSTRACT OF THE THESIS

HUMAN RADIATION EXPOSURE TOLERANCE AND EXPECTED EXPOSURE DURING COLONIZATION OF THE MOON AND MARS

by

Lonnie Joseph Parker

American Public University System, June 26, 2016

Charles Town, West Virginia

Professor Nancy Taylor, Thesis Professor

The future colonization of the Moon and Mars will require a careful selection of early colonists. This paper evaluates the current evidence of the effects of radiation on the human body and compares resistance levels by gender and age. Acute and cumulative radiation exposures from both natural and human-made sources are compared with demographic factors to determine what should be considered in crew assignments for long-term space voyages and early colonization efforts. The types and effects of radiation are reviewed, as well as types of shielding and expected exposures from travel to possible colonization sites and on the surface during construction of shelters and habitats. The maximum cumulative radiation exposure is evaluated by sex and age to determine who should be sent on the first missions to build shielded
infrastructure and habitats. This study indicates that older subjects exposed to high dose radiation have a much lower drop in life-expectancy than younger subjects with those past child-bearing ages approaching middle age, 45 to 55, having the highest survival rates with the least number of lost years. The allowable cumulative radiation exposure is also much higher for older workers allowing a more extended and productive work schedule. While younger astronauts may arguably be able to maintain a higher workload their risk of cancer and shortening of life expectancy is much greater than older candidates.
I. Introduction

Who should we send to build the infrastructure for colonies on the Moon and Mars?

Several governments including those of the United States,\textsuperscript{1} India,\textsuperscript{2} China,\textsuperscript{3} and at least two private companies,\textsuperscript{4} are planning the exploration and eventual colonization of the Moon and Mars.\textsuperscript{5} The Earth has a thick atmosphere that absorbs most harmful radiation and a powerful magnetic field that helps shield the surface from cosmic rays. These factors provide a tremendous amount of protection. Mars, on the other hand, has an atmosphere 1/1000\textsuperscript{th} as thick as Earth’s\textsuperscript{6} and the Moon’s is even thinner.\textsuperscript{7} The Earth has a powerful magnetic field generated by its molten core.\textsuperscript{8} Both the Moon and Mars are smaller, have cooled, and have no significant magnetic field.\textsuperscript{9} The first colonists will be exposed to much higher levels of radiation living on these bodies than they would experience on Earth as they build the shielded tunnels and habitats for the colonists who will come later.\textsuperscript{10} This paper will address the question of who should be sent first to build the infrastructure of the colony. The term year used within this paper indicates 365 Earth days.

It will be necessary to evaluate incidents of human exposure to high levels of radiation as well as places on Earth where residents experience higher levels of ambient radiation to make this determination. The expected radiation exposure of astronauts traveling to and living on the Moon and Mars will be calculated for different travel times and will assume a permanent colonization effort, possibly without a planned return. The current direct data on radiation levels

\begin{itemize}
  \item \textsuperscript{1} Wiener-Bronner \textit{Here’s NASA’s three-step plan to colonize Mars} 2015
  \item \textsuperscript{2} Sharma \textit{Why Indians want to settle on Mars} 2014
  \item \textsuperscript{3} Cerullo \textit{China to Colonize Mars earlier than NASA; will Russia join?} 2016
  \item \textsuperscript{4} Musk \textit{The Case for Mars} 2015
  \item \textsuperscript{5} NASA \textit{Journey to Mars} 2015
  \item \textsuperscript{6} Williams \textit{Mars Compared to Earth} 2015
  \item \textsuperscript{7} Sharp \textit{Atmosphere on the Moon} 2012
  \item \textsuperscript{8} Algar \textit{Scientists Discover Earth’s ‘Invisible’ Shield Protecting Us from Radiation} 2015
  \item \textsuperscript{9} Algar \textit{Scientists Discover Earth’s ‘Invisible’ Shield Protecting Us from Radiation} 2015
  \item \textsuperscript{10} Barry \textit{Radioactive Moon} 2008
\end{itemize}
absorbed by astronauts is limited to the Apollo missions, as this is the only instance to date of humans leaving low Earth orbit. The Apollo spacecraft were incredibly well designed for their time, though some parts of the outer skin were as thin as 0.03cm, as thin as a modern soda can. The Saturn V rocket is unmatched, even today, in its ability to transport payload to orbit. This paper will assume similar technology will be used and the radiation absorbed by the Apollo astronauts will be used to calculate the radiation exposure expected by colonists traveling to the Moon. Several new technologies to protect astronauts will be described but not factored into the final analysis as their feasibility has not been determined. The aforementioned rates have been correlated with equivalent exposures from, Hiroshima,\textsuperscript{11} Nagasaki,\textsuperscript{12} and Chernobyl,\textsuperscript{13} comparing and contrasting by age, sex and other factors, to determine the optimal crew for initial colonization to each of these destinations. The results have been analyzed by mixed methods using both quantitative analysis of the data and qualitative analysis of the comparisons. These correlations will be used to guide the development of proposed selection criteria for the first permanent colonists of the Moon and Mars so as to optimize survival and to minimize morbidity.

The different studies will be standardized to the equivalent dose in Sieverts, defined as the effective dose of a joule of energy per kilogram of recipient biological mass of ionizing radiation,\textsuperscript{14} with the cumulative exposure rates correlated by several demographic factors. This unit will standardize across all types of radiation, alpha, beta, ultraviolet, X-ray, gamma and cosmic, as Sieverts. It is important to note that some types of radiation, ultraviolet and alpha specifically, do not penetrate very far into the skin, while X-rays have variable penetration depending on their energy and gamma rays will always have the energy to penetrate through the

\textsuperscript{11} CNSCU Hiroshima and Nagasaki: The Long Term Health Effects 2012  
\textsuperscript{12} Upton Hiroshima and Nagasaki: Forty years later 1984  
\textsuperscript{13} UNSCEAR Sources and Effects of Ionizing Radiation 2008  
\textsuperscript{14} Merriam Webster Dictionary, \url{http://www.merriam-webster.com/dictionary/sievert}, 2016
human body. It can take up to 1.3 feet of lead to block high energy gamma rays.\textsuperscript{15} Figure 1 shows the relative penetration of Alpha, Beta and Gamma Rays and that they can be blocked by different types of materials. Some radiation, like neutron radiation, require specific shielding materials. This will be discussed in a later section on nuclear power reactor emissions.

\textsuperscript{15} CNSTI \textit{Protecting Against Exposure} 2015
II. Literature Review

Types of Radiation

What is radiation and how does it damage the human body? Radiation is the presence of high-speed atomic or subatomic particles. The particles can be photons in the form of normal light, ultraviolet, X-ray, or gamma radiation. Low frequency photons are generally harmless to the human body. Light that we use in our homes is a type of radiation, but the photons in visible light do not have the energy to knock electrons off of atoms, therefore it is nonionizing radiation. Lower frequency photons, like microwaves, can be used to heat materials but do not normally ionize them. High frequency photons however, starting with ultraviolet, can penetrate into cells and cause damage. Radiation capable of damaging cells is referred to as ionizing radiation and can come from several sources. Any photon of sufficient energy (high frequency), will be able to cause damage to living tissues. Other types of radiation will be discussed in depth below.

Photons are packets of energy and have no rest mass. Other forms of radiation have a physical rest mass and are made of high-speed particles like electrons, protons, atomic nuclei and other physical particles. Early scientists did not understand the fundamental properties behind radiation as well as we do today and categorized types of radiation in the order they were discovered using the Greek alphabet. Alpha radiation was the first to be discovered. On Earth it is usually the result of radioactive decay. A radioactive atom will spontaneously decay into an atom with a smaller nucleus and a different element, and will usually eject two neutrons and two protons in the process. The two protons and two neutrons combine and become a helium nucleus, which is ejected at high speed. Scientists called this high speed helium nucleus an alpha.

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16 Rask Space Faring: The Radiation Challenge
17 Curtis Introduction to Ionizing Radiation 1999
18 Koks What is the mass of a photon? 2008
19 Turner Atoms, Radiation, and Radiation Protection 1995
The next particle discovered, also from radioactive decay, turned out to be a high-speed electron and was called, beta radiation. Gamma rays were discovered after X-rays but were called Gamma anyway. X-rays and Gamma rays are both just high energy photons\textsuperscript{21}.

There are several natural sources of radiation, the greatest exposure comes from Radon gas. This gas is produced deep in the Earth from the decay of larger radioactive atoms. It is a noble gas, combining with nothing, and rises up through the Earth. It is concentrated in enclosed areas such as basements and well insulated homes. It is released at high levels in some areas of the planet.\textsuperscript{22} This is one radiation hazard that will not be increased in space but may be an issue on the Moon\textsuperscript{23} and Mars.\textsuperscript{24} Medical radiation exposure will probably not be a factor in early space travel and colonization though some way to take basic X-rays may be necessary to evaluate bone density and fractures after injury. There may be exposure from radiation sources on board if the ship uses nuclear power sources such as radioisotope thermal generators or fission power reactors.\textsuperscript{25} These potential radiation sources will be discussed but our calculations will assume standard chemical rocket engines with solar and fuel cell power generation. Secondary radiation from cosmic ray impacts will be discussed and considered. Terrestrial sources of radiation in the United States, compiled by the National Council on Radiation Protection and Measurements (NCRP), and other sources are evaluated next. These sources vary greatly, for instance, people who fly frequently on commercial airlines experience increased radiation from reduced atmospheric shielding at high altitudes. More impoverished nations have less exposure to medical radiation exposures such as X-rays. Higher elevation cities like Denver, Colorado, USA

\textsuperscript{20} Tate *What is Alpha Radiation* 2009
\textsuperscript{21} NASA *Understanding Space Radiation* 2002
\textsuperscript{22} Zielinski *Mapping of Residential Radon in the World* 2014
\textsuperscript{23} Powell *Lunar Flash Mystery Solved* 2007
\textsuperscript{24} Jones *Radon leaks could reveal water on Mars* 2003
\textsuperscript{25} Newhall *History of Space Nuclear Power* 2015
and Quito, Ecuador, SA have higher levels of ambient radiation exposure than a city at sea level like Miami or Houston due again to the increased altitude and decreased atmospheric shielding.\textsuperscript{26}

There are several sources of radiation on Earth. The sources for the United States are representative of most industrialized nations and are illustrated below. All of these sources will be different on the Moon or Mars. The average annual exposure in the United States is about 3.6mSv.

The average annual radiation exposure in the US is illustrated in Figure 2.\textsuperscript{27}

Figure 2: Sources of Radiation Exposure in the United States\textsuperscript{28}

Sources of radiation exposure in the United States are illustrated below. Radon goes is shown making up 55% of radiation exposure in the US. The next largest source is medical at 15%. Natural radionuclides in the body are third at 11%. Terrestrial radiation from radioactive materials in the Earth itself, like thorium and uranium, make up 8%. Cosmic radiation that makes it through the atmosphere contributes 7%. Consumer products, such as smoke detectors, clocks, old camera lenses and televisions, sun lamps, ceramics, glass etc, contribute 3%. Cosmogenic radiation is when a cosmic ray strikes another atom, changing its nucleus, and making it radioactive, this type makes up 0.3% of the total. The last contributor is nuclear fuel from reactors in the nuclear fuel cycle that contribute 0.014%. *(1 millirem = 0.01 millisievert)

\textsuperscript{26} Serrano \textit{EXTREME EVENTS OF SOLAR RADIATION IN QUITO: A RELATION WITH TEMPERATURE AND CLIMATE CHANGE} 2014
\textsuperscript{27} NCRP Ionizing Radiation Exposure of the Population of the United States 1987
\textsuperscript{28} NCRP Ionizing Radiation Exposure of the Population of the United States 1987
The relative exposure rates for different parts of the Earth can be quite different, see figures 2 and 3. The above graph from a 1987 NCRP report places the US average annual exposure at 3.6mSv supported by the 1985 study by C.R. Nave.

Figure 3: Relative Radiation Exposure Rates

Figure 3 shows that, converting from millirem to millisieverts, the maximum allowed occupational exposure was 50mSv. The natural exposure from mountainous areas in Brazil was an 12.5mSv, hospital radiologists received an added 5mSv annually, and diagnostic medical procedures caused 0.8mSv. Nuclear power plant workers receive the least with a statutory maximum of 0.05mSv annually.
How is Radiation Measured?

Measuring Radiation

There are many ways to measure radioactivity. Some of the units of measure include the Rad, Rem, Gray, Curie, Roentgen, Becquerel, and Disintegrations per second or Dps. Radiation can be measured by dose, which is energy absorbed per gram of matter as in Sieverts or by exposure, as in Roentgen. The different units used to measure radiation and their relationship to each other can be confusing at times.

A Roentgen (R), again, is a measure of exposure, the metric equivalent is the coulomb/kg of air. 3876R is equal to 1 C/kg. A Rad is a measure of dose, in fact it stands for Radiation Absorbed Dose, and is defined as the energy imparted to a defined mass of tissue. Dose is usually not absorbed uniformly and can be selectively taken up at different rates by different organs. A REM (Radiation Exposure Man) is a dose equivalent measure for biological tissue, the metric equivalent is the Sievert. The Sievert takes into account the effect of the radiation on living tissue and can be compared across several types of radiation. These relationships are illustrated below in Table 1.
Table 1: Ionizing Radiation Measurements and Their Relationships

<table>
<thead>
<tr>
<th>Ionizing Radiation Measurements and Their Relationships</th>
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<tr>
<td>From Sprawls, Radiation Quantities and Units, 2011</td>
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The different types of radiation can be described several ways in either conventional or SI units. Photonic radiation has three properties. Frequency, wavelength and speed.

The speed is always the same for light traveling a vacuum therefore all photons traveling through space are moving at the same speed denoted as c. Multiplying the photons wavelength by its frequency always equals the speed of light therefore from the frequency you can easily derive the wavelength and vice-versa. Photonic radiation is given then either by its frequency or wavelength. This would not help with particle radiation however as it can go any speed and we would have to know the particles rest mass or current momentum to calculate how damaging it would be. A radioactive material that is decaying to lighter elements can be described in disintegrations per second but this unit is meaningless to photons. All these types of radiation have been quantified and their effects on living tissue equilibrated to where we can look at how much radiation is hitting you (Exposure), roentgen and C/kg, how much is being absorbed (Dose), Rad or Gray, or how much damage it will do (Dose Equivalent), Rem and Sievert. The last two are used to determine the effect on the human body.

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<thead>
<tr>
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<th>Conventional</th>
<th>SI</th>
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<tr>
<td>Exposure</td>
<td>Roentgen</td>
<td>Coloumb/kg of air C/kg</td>
</tr>
<tr>
<td>Dose</td>
<td>Rad</td>
<td>Gray</td>
</tr>
<tr>
<td>Dose Equivalent</td>
<td>Rem</td>
<td>Sievert</td>
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For the purposes of this paper we will use the Sievert or supply the conversion factor from the studied unit to the Sievert for equivalent comparison.

The Sievert is a measure of the amount of radiation absorption by the human body. It takes into account the relative biological effectiveness$^{31}$ of ionizing radiation of all types. This paper will report radiation levels in millisieverts, when other units are used a conversion will be

$^{31}$ Clement Fundamentals of Space Medicine 2011
provided. One millisievert is equal to 10 ergs of energy of gamma radiation transferred to one gram of living tissue.

Galactic cosmic radiation, GCR, is radiation coming into our solar system from other star systems.\textsuperscript{32} This radiation is mostly very fast moving atoms from super novae and other energetic events. The atoms are very dangerous to living cells and electronic equipment. The amount of GCR that reaches the surface of the Moon is reduced by increased sun activity as the sun’s solar wind sweeps the incoming GCR away from the surface of the Moon and Earth and protects it somewhat.\textsuperscript{33} This causes a variation of 110mSv during solar maximum to as high as 380mSv during solar minimum.\textsuperscript{34}

The effect of radiation on the human body has been studied since the days of Marie Currie. She died from a blood disease called aplastic anemia, which is a known consequence of radiation exposure.\textsuperscript{35} Radiation is almost always present in our environment. There are natural levels of thorium and radium in the ground and coal powered electrical plants release these into the air. In fact, more radiation is released into the environment by coal powered electrical plants than nuclear powered plants. The human body has evolved with this radiation and has several repair mechanisms, discussed later, to repair radiation damage.

Acute Radiation Exposure

The lethal dose of radiation exposure is considered by most sources to be 10 Sieverts or 10,000mSv. Nuclear workers are normally limited to a yearly dose of 50mSv though this was

\textsuperscript{32} NASA Space Faring: The Radiation Challenge 2008
\textsuperscript{33} Barry Radioactive Moon 2008
\textsuperscript{34} Reitz Radiation exposure in the Moon environment 2012
\textsuperscript{35} Bagley Marie Curie: Facts and Biography 2013
raised to 250mSv during the Fukushima disaster. The maximum allowed international dose for emergency workers taking life-saving actions is 500mSv.

There have been several radiation disasters since the advent of atomic power that have given us an insight into acute radiation sickness. The Fukushima Daiichi disaster was caused by a tsunami generated by an offshore Earthquake that damaged a nuclear power plant causing the three cores to it to overheat and meltdown. This released radiation into the surrounding area on 11 March 2011. 19,594 people worked at the site from 11 March 2011 until 31 December 2011. 167 workers received doses of over 100mSv. Of these 167 135 received between 100 to 150mSv, 23 had received between 150 and 200mSv, 3 had received 200 to 250mSv and 6 had received over 250mSv (309 to 678mSv). None of these workers experienced acute radiation syndrome.

These workers were all carefully monitored for radiation exposure and were rotated out based on their readings. Older workers volunteered to work longer at the site than younger workers.\textsuperscript{36}

The nuclear disaster at Chernobyl exposed 134 workers on-site at the time of the accident to between 800mSv to 16,000mSv. 28 died within the following three months and another 19 over the next seven years of cancers that could not clearly be linked to their exposure.\textsuperscript{37}

Radiation Sickness

In a short time, a sufficient dose of radiation, about 1,000mSv, causes acute radiation sickness, and a dose of 10,000mSv is often fatal.\textsuperscript{38} When someone receives enough radiation to make them almost immediately ill it is called acute radiation sickness. This condition is very

\textsuperscript{36} Lah Japanese seniors volunteer for Fukushima ‘suicide corps’ 2011
\textsuperscript{37} UNSCEAR Health Effects Due to Radiation from the Chernobyl Accident 2008
\textsuperscript{38} Clement Fundamentals of Space Medicine 2011
debilitating and would certainly interfere with a crew’s ability to function. The highest risk of this level of radiation exposure would be from solar or galactic events producing a dramatic increase in radiation. These events are caused by coronal mass ejections from the sun or from nearby clusters of massive stars. These events could expose the crew to acute radiation sickness and protocols would need to be developed to deal with this eventuality. The symptoms of acute radiation exposure can be easily confused with other maladies. Radiation monitoring devices will be necessary, both in the ship as a whole and on the individual astronauts, with alarms to notify the crew of hazardous levels. The symptoms of acute radiation sickness are shown below.

Table 2: Acute Radiation Sickness

<table>
<thead>
<tr>
<th>Dose (Sv)</th>
<th>Probable Medical Effects</th>
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<tr>
<td>0.1 – 0.5</td>
<td>No effects except minor blood changes.</td>
</tr>
<tr>
<td>0.1 - 1</td>
<td>5 to 10% of crew will experience nausea or vomiting; fatigue for 1 to 2 days; slight reduction in white blood cells.</td>
</tr>
<tr>
<td>1 - 2</td>
<td>25 to 50% of crew will experience nausea and vomiting; with some other symptoms; 50% reduction in white blood cells.</td>
</tr>
<tr>
<td>2 – 3.5</td>
<td>75 to 100% nausea, vomiting, fever, anorexia, diarrhea and minor bleeding; 75% reduction in all blood elements; 5 to 50% of crew will die.</td>
</tr>
<tr>
<td>3.5 – 5.5</td>
<td>100% nausea, vomiting, fever, bleeding diarrhea and emaciation. Death of 50 to 90% of crew within 6 weeks. Survivors require 6-month convalescence.</td>
</tr>
<tr>
<td>5.5 – 7.5</td>
<td>100% nausea and vomiting in 4 hours; 80 to 100% of crew will die.</td>
</tr>
<tr>
<td>7.5 – 10</td>
<td>Severe nausea and vomiting for 3 days. Death of entire crew within 2.5 weeks.</td>
</tr>
<tr>
<td>10 – 20</td>
<td>Nausea and vomiting within 1 hour. 100% of crew will die within less than 2 weeks.</td>
</tr>
<tr>
<td>45</td>
<td>Incapacitation within hours. 100% of crew will die within 1 week.</td>
</tr>
</tbody>
</table>

Acute radiation exposure will first cause nausea and vomiting but can, if severe, cause death.

39 Fox Microscopic "Timers" Reveal Likely Source of Galactic Space Radiation 2016
40 Clement, Fundamentals of Space Medicine 2011
Cumulative Radiation Exposure

The maximum cumulative dose is defined differently by different sources. This paper will consider the standards set by the Nuclear Regulatory Commission and NASA. Calculating the cumulative dose requires the continuous wearing of a monitoring device. These devices are sometimes badges of unexposed film in a sealed container. When radiation passes through the badge it exposes the film.\(^{41}\) The film can later be developed and the degree of exposure calculated. More advanced devices have scintillation detectors with variable degrees of shielding. These can track and record different exposure levels of different types of radiation. There is even an attachment that can be put on a smartphone.\(^{42}\) The cumulative dose does not necessarily cause immediate illness but increases the risk of cancer and can considerably shorten life expectancy. The effects of radiation on the human body have been well studied from natural exposures, industrial exposures, and nuclear accidents.\(^{43}\) Nuclear reactors, both on land and in naval vessels,\(^{44}\) have been used for over sixty years and careful records kept of exposures and health consequences.\(^{45}\) These records have been helpful in quantifying cumulative radiation exposure and their long-term effects on humans.

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\(^{41}\) Orders Personnel Monitors: Radiation Dosimeters 2016

\(^{42}\) Polimaster Radiation Detection on your Mobile 2016

\(^{43}\) Levenson Realistic Estimates of the Consequences of Nuclear Accidents 1981.

\(^{44}\) Conca America’s Navy The Unsung Heroes of Nuclear Energy 2014

\(^{45}\) World Nuclear Organization Safety of Nuclear Power Reactors 2016
Radiation Effects on the Human Body

Ionizing radiation hits an atom in the body hard enough to knock off electrons. This breaks the bonds that the atom shares with other atoms within a molecule. The breaking of this bond causes the molecule to change to one or several different molecules. This reaction can damage the cell’s ability to function by destroying DNA, cell membrane components, and other molecules important to the cell. Another type of radiation is solid particle radiation. This includes beta rays, which are high speed electrons, alpha rays, which are high speed helium nuclei, and cosmic rays, which are all types of atomic nuclei traveling at high speeds, some near the speed of light. The very heavy atoms such as iron are the most damaging. A single iron nucleus traveling at near light speed can cause severe damage to the human cell.

Cells are composed of a cell membrane holding sea water like cytoplasm. Within the cytoplasm are several structures called organelles, these organelles carry out different functions for the cell. The most important of these in regards to radiation injury are the nucleus and the mitochondria. The nucleus contains the autosomal DNA. Autosomal DNA carries the instructions for every protein, enzyme, cell, tissue and organ in the body. This DNA is composed of phosphate, deoxyribose and four molecules called bases. These bases are either thymine, adenosine, guanine or cytosine. The order of these molecules determine the genetic code of an organism. This code is read in three letter “words” called codons. The order of these letters is critical to the proper functioning of the cells. Radiation travelling through the nucleus can disrupt these bases, converting one to another or knocking one out entirely. This type of

46 NASA Why is space radiation an important concern for human spaceflight? 2016
47 Chancellor Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit 2014
48 NIH What is DNA? 2016
damage changes the reading of codons and results in abnormal and sometimes nonfunctional proteins. If enough of this damage occurs the cell may self-destruct, a process called apoptosis, or it may become cancerous.49

All cancer is caused by errors in DNA.50 DNA tells a cell where to be and how to function. Human DNA is stored in two copies of 23 chromosomes, bundles of DNA, where it is rolled up tightly to protect it when not in use. When the DNA is unrolled to be read it is most vulnerable to damage. Cells that divide frequently have their DNA unrolled the most. These cells are most vulnerable to radiation injury. This is one reason why radiation is so devastating to young, growing organisms. A fetus developing in the womb can be severely damaged or killed by an X-ray or CT scan that would not harm an adult. In adults most cells are dividing slowly but a few tissues are still rapidly dividing. Cells in the nervous system were thought at one time to not divide at all in adults but more recent research shows that some brain cells continue to divide and form new neurons in a few areas of the brain. Other tissues in the adult human body have rapidly dividing cells throughout life.

The cells of the gastrointestinal tract, the esophagus, stomach, intestines and colon are rapidly replacing themselves. These tissues are therefore more easily damaged by radiation and some of the first signs of radiation poisoning are nausea, vomiting and gastrointestinal bleeding. The tissues of the muscle and bone are not rapidly dividing in adults but inside some bones is the bone marrow. The bone marrow produces the blood cells that carry oxygen, fight infection and help blood clot after injury. The bone marrow cells that do this are stem cells.51 Stem cells are cells that stay active even in adult bodies. They produce other cells that the body needs to

49 Alberts Programmed Cell Death (Apoptosis) 2002
50 ASOC The Genetics of Cancer 2015
51 Testa Long-term bone marrow damage in experimental systems and in patients after radiation or chemotherapy 1985
replace. If the DNA in these cells is damaged but not enough to kill the cell it may start overproducing just one type of blood cell. These will crowd out production of the other cells leading to medical conditions that can be fatal. Aplastic anemia occurs when too many of the stem cells producing erythrocytes, red blood cells, are damaged and not enough new red ones are made. Leukemia is when the stem cells produce too many white blood cells.

Radiation Shielding

Figure 4: Basic shielding materials and their effectiveness per gram/cm$^3$ for Galactic Cosmic Radiation$^{52}$

The ability of different materials to block GCR is shown in Figure 5. Aluminum is the least effective, water is 15% more effective at 10g/cm$^2$ but liquid hydrogen far surpasses both 250% better than water and 288% better than aluminum at 10g/cm$^2$

$^{52}$ Johnson Space Center Guidance on Radiation Received in Space Activities 1989
Atmospheric Shielding

Radiation can be blocked and absorbed by several different materials. Any substance, gas, liquid or solid, can absorb or block different types of radiation. Some types of radiation are easy to block. Alpha particles, which are again high speed helium nuclei, can be blocked by a sheet of paper. It is most dangerous if ingested. Beta particles, high speed electrons, can be stopped by just two inches of wood. Most gamma rays, high energy photons, can be stopped with about 0.635cm to 1.35cm of lead depending on the photons energy. Differences in planetary atmospheres and shielding devices and materials available to astronauts will be discussed below.

The gases in a planet’s atmosphere can block most harmful radiation, such as the Earth’s or it can block very little of it, like Mars. The Earth’s atmospheric composition is 78% nitrogen, 21% oxygen, <1% water, <1% argon, and 0.038% carbon dioxide. There are various trace gases but these are the most important with the exception of ozone. Oxygen is O₂, ozone is O₃. It is created in the upper atmosphere by the interaction of high energy particles from the sun and regular oxygen molecules, O₂. Ozone is very good at absorbing ultraviolet light.⁵³ Ultraviolet light is composed of photons with just a little too small of a wavelength to be seen by the human eye. It is the weakest level of photon energy capable of damaging living cells and is a type of ionizing radiation. It causes sunburns, cataracts and skin lesions in humans on Earth and, with prolonged exposure, can cause serious cancers.⁵⁴

Without the ozone layer of the Earth protecting us the level of ultraviolet radiation would be much higher. Mars has no appreciable oxygen in its atmosphere and, even though it is farther from the sun, will expose astronauts to a much higher ultraviolet levels. Ultraviolet radiation

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⁵³ Allen Ultraviolet Radiation: How it Affects Life on Earth 2001
⁵⁴ Narayanan Ultraviolet Radiation and Skin Cancer 2010
also speeds the breakdown of many materials including plastics and this will have to be taken into account when designing equipment for the colonization of Mars. The Moon possesses only a very tenable atmosphere\textsuperscript{55}, very close to a pure vacuum, and ultraviolet radiation there will be even higher than on Mars due to the Moon’s closer proximity to the Sun. Transparent materials will have to be made opaque to ultraviolet light to protect humans from this danger. Many materials transparent to visible light are opaque to ultraviolet light. These materials can also be very durable, which is important considering the risk of orbital debris collisions. NASA has developed a type of glass called (REAL glass\textsuperscript{TM}). REAL stands for Rare Earth Aluminum oxide\textsuperscript{56}. It is a type of metallic glass where the metal atoms, instead of forming crystals, form random assemblies and are therefore much more resistant to fracture than normal metals. They can be made in bulk on Earth using special electrostatic levitators that suspend the glass while it is being heated by a laser to melt and combine the materials. This would be much easier to produce in space but even now we can produce extremely strong and durable materials opaque to ultraviolet and perfect for spacecraft windows.\textsuperscript{57}

Magnetic Shielding:

The Earth possesses another form of radiation protection provided by its natural magnetic field as previously discussed\textsuperscript{58}. Solar and cosmic non-photonic radiation is composed of protons and charged nuclei. Most of the solar radiation is composed of charged hydrogen and helium nuclei while cosmic radiation will contain much larger nuclei, such as iron as mentioned before. These charged particles, or ions, can be moved by magnetic fields. The Earth happens to generate a large magnetic field of about 30 to 60 microteslas. This magnetic field stretches far

\textsuperscript{55} NASA Is there an atmosphere on the Moon? 2016  
\textsuperscript{56} Weber Single-Phase Rare-Earth Oxide/Aluminum Oxide Glasses 2006  
\textsuperscript{57} Roy A New Class of Glass 2016  
\textsuperscript{58} McCormac Radiation Trapped in the Earth’s Magnetic Field 1965
out from the Earth and deflects much of the charged radiation that approaches Earth.\(^{59}\) Mars is smaller than Earth and its core has cooled causing it to lose its magnetic field. Solar and cosmic radiation exposure will therefore be much higher there. The Moon has cooled and also lost its magnetic field and is closer to the sun making the risk of radiation bursts from solar flares very high. Solar flares are caused by magnetic lines of force in the sun breaking free and travelling away from the sun at very high speeds. These magnetic fields carry plasma from the sun’s surface with them. These flares can hit the Moon and would be deadly to any astronauts on the surface shielded only by their suits. Some are strong enough to kill a crew even if they are inside current spacecraft. This is why the ISS has a “storm shelter”\(^{60}\) that the crew flees to when there is a higher than normal risk of radiation injury.

No spacecraft has yet had the energy resources required to create a magnetic field around it to protect the crew but when more powerful solar, nuclear or fusion generators are available it should be possible to do so.\(^{61}\) Figure 5 below shows a proposed design for a radiation shield using superconducting magnets. This system would require an enormous amount of energy but could prove to be the only practical way to shield colonists from galactic cosmic radiation. Simply using thicker metallic shielding will increase secondary radiation and hydrogen or water shielding would be prohibitively massive.\(^{62}\)

\(^{60}\) Roylance *Space Station Astronauts take Shelter from Solar Radiation* 2000

\(^{61}\) Cartlidge *Magnetic shield could protect spacecraft* 2008

\(^{62}\) Westover *Magnet Architectures and Active Radiation Shielding Study* 2012
It is possible that future technologies may be able to use higher temperature light weight superconducting magnets with niobium titanium alloy embedded in a copper matrix like those being used by Dr. Chang-Diaz in his Variable Specific Impulse Magnetoplasma hydrodynamic Rocket (VASIMR®) engine which can operate at 6 Kelvin. It may be possible for a ship to carry these advanced magnets in a low power mode and, upon detection of high radiation levels, could divert all available power to the magnetic shield system. A nuclear powered spacecraft may be able to sustain a high powered shield system while still having enough power for propulsion, life support and other functions. This type of system could vary the power output depending on the radiation level. This shielding system only works for charged particles, high

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63 Chang-Diaz What is the state of the superconducting magnet technology used in the VASIMR engine? 2016
energy atomic nuclei that have lost or gained electrons, and would not be effective against X-rays and gamma rays. Charged particle radiation, solar and galactic, is one of the major threats to space flight and any system that could efficiently reduce the risk would be well worth considering. Solar events called Coronal Mass Ejections or CMEs occur when magnetic lines carrying massive amounts of plasma break free from and are ejected by the sun. These loops of plasma have tremendous currents coursing through them creating the magnetic field that holds the plasma together.64 When one of these strike the Earth or a spaceship it can instantly produce fatal radiation levels and destroy equipment.

The only practical defense for the entire ship would be a magnetic shield device. Space craft electrical systems are designed to withstand common solar events and a crew storm shelter could be used temporarily. The international space station crew goes to a more heavily shielded area of the station during solar events such as the Destiny Laboratory Module or the Russian built Zvezda Module.65 These solar events can generate extreme variations in radiation levels, see figure 6 below.

Figure 6: Solar Proton Events During the Apollo Program66

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64 Space Radiation Analysis Group What is Space Radiation 2016
65 Phillips Who’s Afraid of a Solar Flare? 2005
66 JSC Spaceflight Radiation Health Program at JSC 2010
Solid Materials Shielding

Many different materials are able to absorb radiation and could be used to protect colonists. Lunar regolith and Martian soil could be used as shielding. Soil is quite effective for this purpose with several feet protecting even from gamma rays.\(^67\) The problem with getting to the Moon or Mars is that carrying several feet of soil around the craft is not currently feasible. Certainly if we could build our ships on the Moon its lighter gravity would allow us to orbit ships much more massive than we can ever hope to from Earth. Until that time mass and volume will be at a premium and it will be necessary to find the optimal shielding for each spacecraft application. Several alloys of light metals are currently used for structural support and shielding for spacecraft. The colonization of the Moon would allow much heavier shielding to be used on colonization spacecraft meant for Mars as the power needed to lift mass out of the Moon’s gravity well is much less than that of Earth. The Moon could be used to construct large transport ships, shielded by titanium alloys produced on the Moon, and also by water extracted from the Moon’s polar craters. This would dramatically reduce the radiation exposure experienced by the crew on their voyage from the Moon on to Mars. The Moons of Mars, Phobos and Deimos, could also be used to produce spacecraft and materials to use on Mars if they have a composition of titanium, iron and nickel. Iron and nickel can be used to make very stable and strong alloys of steel.\(^68\)

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\(^{67}\) Miller Lunar soil as shielding against space radiation 2009
\(^{68}\) Donachie Handbook of Engineering Fundamentals 2009
Water Shielding:

Hydrogen is an excellent absorber of radiation therefore water is an excellent shielding material. It does however weigh 1 kg, or 2.2 pounds, per liter. This makes it difficult to take into orbit in quantities necessary for shielding. Water is necessary to have on board and a system distributing that water into the habitat walls, such as those being developed by Bigelow Aerospace, would be very efficient. It would take about 1 meter of water to shield the crew from all but the most energetic cosmic ray particles. This meter, distributed over the habitat and work areas of the ship, would result in a tremendous amount of mass. It would be very difficult to lift this much mass out of Earth’s gravity well. In the future it may be possible to use the water on the Moon or from near-Earth asteroids to provide this shielding for deep space missions but for now even a few centimeters would dramatically reduce the amount of exposure experienced by the crew. Since water is always necessary on a manned spacecraft this water should be distributed as much as possible around the crew areas. All current designs use water tanks that provide little crew shielding. Distributing the water around the crew area would require a completely novel redesign or the use of inflatable systems with water in the exterior shell. Clean drinking water would have to be separated from gray water and a filtration system used to recirculate and conserve water. These systems would have to have pumps to shift water mass from one area to another to prevent an unequal distribution while at the same time not mixing the gray water with clean.

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69 Lieberman The Future of Construction in Space 2015
70 Durante Physical basis of radiation protection in space travel 2011
Plastic Shielding

Materials with lots of hydrogen, like water, are excellent absorbers of radiation. Plastics are long synthetic molecules of mainly carbon and hydrogen. These materials are excellent at shielding humans and have the added benefit of being lightweight, inexpensive and easy to shape and mold. Plastic can be very heat resistant also as the information in table 3 taken from Craftech Industries illustrates.\textsuperscript{71}

Table 3: The Temperature Resistance and Tensile Strength of Plastics that Could Be Used for Radiation Shielding\textsuperscript{52}

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Tensile strength at 26C</th>
<th>Flexural strength at 26C</th>
<th>Max service temperature</th>
<th>Melting Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vespel</td>
<td>8,750 psi</td>
<td>16,000 psi</td>
<td>300 C</td>
<td>None</td>
</tr>
<tr>
<td>Torlon</td>
<td>27,847 psi</td>
<td>35,390 psi</td>
<td>260 C</td>
<td>None</td>
</tr>
<tr>
<td>Ryton</td>
<td>21,755 psi</td>
<td>25,800 psi</td>
<td>218 C</td>
<td>None</td>
</tr>
<tr>
<td>Noryl</td>
<td>9,200 psi</td>
<td>7,400 psi</td>
<td>105 C</td>
<td>154 C</td>
</tr>
</tbody>
</table>

Table 3 shows the durability of several types of plastic that could be used to build the spacecraft providing a light-weight and strong heat-resistant structure with excellent radiation absorbing properties. Compared to aluminum polyethylene is 50% better at blocking solar flares and 15% better for cosmic rays while having the heat resistance and strength of the plastics shown above. Barry Plastic Spaceships 2005

\textsuperscript{71,52} Gerard Don’t sweat it! These 4 High Temp Plastics Can Take the Heat 2014
Regolith Shielding

Regolith slab shielding studies show that a thickness of 100cm of Moon soil would reduce the predicted radiation dose to acceptable levels. A solar flare was recorded on the Moon in 1972 that produced a radiation level of 5000mSv at 5cm tissue depth. A NASA study found that 50cm of regolith shielding would have reduced the dose to a non-hazardous level well below 10mSv.\textsuperscript{72} The use of local materials to provide radiation shielding will be critical to colonist success and survival.

Secondary Radiation

Secondary radiation is caused by radioactive particles hitting atoms in shielding, equipment, astronauts, and even the lunar surface, that causes a release of radiation from the impact. This effect is actually increased with heavy metal shielding and is least with the use of liquid hydrogen shielding. This is also called \textit{Bremsstrahlung} or braking radiation. This type of radiation is produced when a charged particle decelerates in the electromagnetic field of an atom’s nucleus. The larger the atom the greater this effect, meaning dense materials like lead produce much more of this radiation than hydrogen or water. The Moon’s heavy cosmic ray exposure causes a considerable amount of secondary radiation.\textsuperscript{73} While metals are excellent for blocking X-rays and low-energy gamma rays a metal walled spaceship would produce much more of this radiation than one with walls made from plastics and filled with water. The denser the material the higher the levels of generated secondary radiation. Lead would therefore be great for blocking photonic radiation but the worst choice to reduce secondary radiation.

\textsuperscript{72} Nealy \textit{Solar Flare Shielding with Regolith at Lunar Base Site} 1988
\textsuperscript{73} Barry \textit{Radioactive Moon} 2005
Ambient Radiation

The average annual radiation dose received on Earth depends upon elevation and ambient radiation sources but averages are 3.6 to 6.2 mSv in the United States from all sources\textsuperscript{74} and 2 to 3 mSv globally.\textsuperscript{75} This makes the average person’s daily dosage about 0.017 mSv. The highest populated ambient radiation level is at Ramsar, Iran, and is the result of hot springs that bring up Radon 226 producing an ambient radiation level of 132 mSv per annum or 0.36 mSv per day.\textsuperscript{76} This is about twenty-one times higher than the US daily average. Over fifty years of carefully collected data has proven that there is no detectable increase in the incidence of cancer with an annual radiation dose of 50 mSv or less.\textsuperscript{77}

The average daily exposure rate on Earth varies greatly depending on where you live. The ambient radiation levels are twice as high in Denver as they are in Houston due to less atmospheric protection at higher elevations. There are also naturally occurring radioactive substances that can greatly effect radiation exposure. Radon is a radioactive noble gas released by the radioactive decay of larger elements deep underground. It can become concentrated in poorly ventilated buildings and basements. Radon-222 is a member of the radioactive decay chain of uranium-238. Radon-220 is formed in the decay chain of thorium-232. Once inhaled Radon will decay and give off alpha, beta and gamma radiation. The Moon and Mars will probably emit some radon gas and possibly some other radioactive materials produced by cosmic ray bombardment. Direct measurements will be necessary to accurately quantify these sources and shielding requirements will have to be adjusted. The current averages for the Earth, the

\textsuperscript{74} United States Nuclear Regulatory Commission Doses in Our Daily Lives 2015
\textsuperscript{75} NASA Understanding Space Radiation 2002
\textsuperscript{76} Mortazavi High Background Radiation Areas of Ramsar, Iran 2016
\textsuperscript{77} McGee Surviving Radiation in Space 2013
Moon, Mars and open space are summarized in the table 4. These averages have been collated from several sources.

Table 4: Annual Ambient Radiation Levels for the Earth, Mars, the Moon and Space

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Mars</th>
<th>Moon</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Total</td>
<td>3mSv$^{78}$</td>
<td>245mSv$^{79}$</td>
<td>438mSv$^{80}$</td>
<td>657mSv$^{81}$</td>
</tr>
<tr>
<td>Daily Average</td>
<td>0.0082mSv$^{82}$</td>
<td>0.67mSv$^{83}$</td>
<td>1.2mSv$^{84}$</td>
<td>1.8mSv$^{85}$</td>
</tr>
</tbody>
</table>

The table shows that the average annual radiation exposure in open space is 219 times more than on Earth while that on the Moon is 146 times more. The surface of Mars would be a little more than 81 times the average annual exposure rate of Earth. The beaches at Guarapari, Brazil produce annual average exposures of 175mSv. This is 58 times more radiation than the average annual exposure rate over the entire Earth.$^{86}$ Ramsar Iran at 250mSv per year is as high as the average on Mars.

Personalized Radiation Risk

Not everyone of the same age and sex has the same risk when exposed to the same radiation levels. Some people are genetically more resistant while others are more vulnerable. A condition known as xeroderma pigmentosum$^{87}$ causes someone to be so susceptible to radiation that even visible light can cause damage to the skin and any amount of UV can cause cancer.

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$^{78}$ Mortazavi, High Background Radiation Areas of Ramsar, Iran, 2016
$^{79}$ Extrapolated from 19
$^{80}$ Extrapolated from 21
$^{81}$ Extrapolated from 23
$^{82}$ Extrapolated from 16
$^{83}$ Gorguipour, The Impact of Solar Particle Events on Radiation Risk for Human Explorers of Mars, 2010
$^{84}$ Anthony, Scientists produce Star Trek-like deflector device for cancer-free interplanetary travel, 2013
$^{85}$ Jurist, Radiation Biophysics and Human Spaceflight, 2015
$^{86}$ Veiga Measurement of natural radioactivity in Brazilian beach sands 2006
$^{87}$ Wilson Synergistic cytotoxicity and DNA strand breaks in cells and plasmid DNA exposed to uranyl acetate and ultraviolet radiation 2014
The opposite is also true where some people have very robust DNA repair enzymes and can tolerate a much higher exposure to radiation before their risk increases commensurately. Dr. Michael Weil at the University of Colorado Cancer Center published an article in Frontiers in Oncology that described methods of evaluating personalized risk. Some cancers are now treated with high energy carbon atoms, basically artificial cosmic rays. These treatments can be very effective at damaging tumors but also put the patient at risk of developing new cancers. Dr. Weil is using mice in his studies, exposing them to high (H) atomic number (Z) high energy (E) ions, abbreviated (HZE), and studying their rates of cancer. Humans and mice share many genes and a very similar physiology. The mice can be studied for gene variants that make them resistant to radiation and these variations can then be searched for in humans. It may one day be possible to insert genes for radiation resistance into the genome of an astronaut but for now available genetic screening should be used to make sure that a candidate is not unusually susceptible to radiation injury.

Radiation Aging

Human aging has several causes, some well-defined, others not yet elucidated. One of the factors related to the speed of aging is something called telomeres. Telomeres are repeated DNA sequences on the end of chromosomes. Each time the cell divides it loses some telomeres. When all the telomeres are gone the cell cannot divide further and replace itself. This is one of the main factors in aging and is called replicative senescence. Most human cells only divide 50 to 100 times before they hit this limit. There appears to be a strong correlation between the number of telomeres a person has and longevity. Frank Cucinotta of Johnson Space Center has found that cosmic rays damage telomeres and speeds up aging. The research conducted by

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89 Smith Replicative senescence: Implications for the vivo aging and tumor suppression 1996
NASA has shown that exposure to iron-nuclei radiation, a chief component of cosmic rays, damages the telomeres of cells much more than gamma rays.\(^{90}\)

Long-term Dementia from Cosmic Rays

There is considerable evidence that cosmic ray exposure causes the build-up in the brain of amyloid plaques, like those seen in Alzheimer’s disease. This condition causes cognitive and memory problems and could seriously impair crew function. The research was performed by placing mice in the path of a particle accelerator and observing the effect on brain tissue.\(^{91}\) There are medications such as Aricept that can reduce the effects but periodic neuropsychological testing will be necessary to detect these changes at the earliest possible stage.

Radiation from Power Sources

NERVA

There are several power systems used in deep space exploration that produce radiation. NERVA stands for Nuclear Engine for Rocket Vehicle Application. It was a compact graphite based nuclear reactor developed in 1963 for the American space program. The Phoebus-2A reactor, a completed test engine, ran for twelve minutes producing 4,000 megawatts of thermal energy. It was canceled in 1973 but the idea has been revitalized recently as an option for deep space travel and is being considered for a Mars mission, as it would considerably reduce the time needed to get there. The unit itself would however produce its own radiation and would have to be shielded to protect the crew.\(^{92}\) This device produces an intense gamma and neutron radiation

\(^{90}\) NASA NASA Investigates ‘Radiation Aging’ Danger Faced by Astronauts from Cosmic Rays 2006
\(^{91}\) Cherry Galactic Cosmic Radiation Leads to Cognitive Impairment and Increased Aβ Plaque Accumulation in a Mouse Model of Alzheimer’s Disease 2012
\(^{92}\) Gunn Application of Proven Rover/NERVA Nuclear Thermal Rocket Technology for Near Future Manned Planetary Missions
field that would require a tungsten and lithium hydride shield to protect the crew. It would also be a good idea to put the liquid hydrogen fuel tanks between the crew and the engine to take advantage of the excellent shielding property of this material.

TOPAZ

The Soviet designed TOPAZ reactors were nuclear power plants developed in 1957 at the Kurchatov Institute of Atomic Energy-Moscow and built and tested in 1961. TOPAZ stands for Thermionic Experiment with Conversion in Active Zone in Russian. It is a compact nuclear power plant first used on the Cosmos 1818 and 1867 surveillance satellites. Two were sold to the United States in 1992. TOPAZ-1 produced 150 kWs of thermal energy and 5 to 10 kilowatts of electrical power with a mass of only 320kg but had a life expectancy of only about 6 months. TOPAZ-2 is heavier at 1061kg but has a 3-year life expectancy. It produces about 6 kWs of electrical power. These systems produce a neutron flux of $1 \times 10^{11}$ neutrons/cm$^2$ and $5.0 \times 10^4$ roentgen of gamma ray flux. This converts to 438,500mSv 18.5 meters from the reactor centerline. A shield of lithium hydride is needed to block the neutrons and stainless steel to block the gamma rays. This system could produce enough electricity to allow for advanced cosmic ray shielding using magnetic fields but, even with shielding, would itself definitely pose an increase in the potential radiation exposure to the crew. Additional mass and design considerations would be necessary to protect the crew from the radiation produced by the device and there is always the possibility of a malfunction or meltdown that could cause severe radiation exposure.

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93 Aftergood *Background on Space Nuclear Power* 1989
Radioisotope Thermoelectric Generator

These systems, also called radioisotope power systems, use the breakdown of radioactive materials to directly produce electricity. The United States has developed seven generations of these and used them in over 26 missions, including the Curiosity Rover and the Cassini spacecraft. These systems produce much less radiation than NERVA or TOPAZ and require less shielding but produce much less power also. They would not be sufficient to power a magnetic radiation shield and would be good for essential systems, backup and emergency power only.\textsuperscript{94} They can however last a very long time. The Voyager 2 spacecraft uses this type of power and has been operating continuously since 1977 and is expected to maintain power and function until 2025 according to the Jet Propulsion Laboratory.\textsuperscript{95}

International Radiation Exposure Standards

Several space-faring nations have developed radiation dose limit standards for their astronauts. These agencies do not all agree on what the limits should be. The Russian, European and U.S. standards will be evaluated\textsuperscript{96}.

-Russian Space Agency (RSA) Dose Limits

There is no age or gender variance for the RSA. They consider 1000mSv the overall cumulative limit for all ages and sexes for full body exposure. They have also developed limits for acute and 30-days exposures for different tissues. The Blood Forming Organs (BFO) are

\textsuperscript{94} NASA Radioisotope Power Systems for Space Exploration 2004
\textsuperscript{95} JPL Voyager, The Interstellar Mission 2015
\textsuperscript{96} Cucinotta Radiation Risk Acceptability and Limitations 2010
limited to 150mSv one-time acute exposure, a 250mSv 30-day limit, and a 500 mSv per year limit. The eyes have a 500mSv 30-days limit, 1000mSv annual limit, and a 2000mSv career limit. The skin has a 1500mSv 30-day limit, a 3000mSv annual limit and a 6000mSv career limit.

-European Space Agency (ESA)

The European Union also has no differentiation by sex or age. The have a 1000mSv overall career exposure limit and separate limits by tissue like the Russians. The BFO 30-day limit is 250mSv and the annual limit is 500mSv. The eyes have a 500mSv 30-day limit and 1000mSv annual limit. The Skin has a 1500mSv 30 day and 3000mSv annual exposure limit.

-United States (NASA)

The United States has a standard for maximum exposure rates over one year that are different for men and women. These limits were developed for spaceflight operations on the Space Shuttle and the International Space Station. The rates of exposure over different periods of time have a large effect on the acute and chronic problems that can arise. The body is able to repair certain levels of radiation exposure, as it has evolved to withstand a certain level of ambient radiation. Limiting the amount of radiation astronauts experience over short periods of time protects them from immediate illness and reduces serious long-term effects. See Table 5 for an analysis of the current one-year mission limits for radiation exposure in males and females based on the age of exposure.
Table 5: One Year Mission Limits from Radiation Risk Acceptability and Limitations

<table>
<thead>
<tr>
<th>Age at Exposure</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>620</td>
<td>470</td>
</tr>
<tr>
<td>35</td>
<td>720</td>
<td>550</td>
</tr>
<tr>
<td>40</td>
<td>800</td>
<td>620</td>
</tr>
<tr>
<td>45</td>
<td>950</td>
<td>750</td>
</tr>
<tr>
<td>50</td>
<td>1150</td>
<td>920</td>
</tr>
<tr>
<td>55</td>
<td>1470</td>
<td>1120</td>
</tr>
</tbody>
</table>

The table shows clearly that older colonists have more than twice the one-year limit as younger colonists.

Mars One Colonist Selection

Mars one is a non-profit organization dedicated to the colonization of Mars. There is much debate over whether or not they have any realistic chance of doing so but they are the only organization that is currently selecting colonists for a future Mars colony. This program plans to crowd-fund the purchase of commercial space launch services like those provided by SpaceX. SpaceX has the current capability to launch capsules for International Space Station re-supply and has stated plans to land a capsule on Mars in 2018. Mars One plans to start sending colonists to Mars as early as 2027. The plan is currently to use the landing capsule for part of the living quarters and also to have inflatable habitats attached to these that can be covered in Martian soil, see figure 7.
The Mars One habitat plan includes using the landing capsules as living space and inflating large greenhouses and other structures to these. The inflatable structures will then be buried under soil to provide radiation protection. This will require considerable hours of unshielded work to accomplish.

Table 6: The Current Pool of Potential Mars One Colonists

<table>
<thead>
<tr>
<th>Age Range</th>
<th>Males selected</th>
<th>Percent of selectees</th>
<th>Females selected</th>
<th>Percent of selectees</th>
<th>Radiation Limits Males/Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 or less</td>
<td>7</td>
<td>14%</td>
<td>6</td>
<td>12%</td>
<td>1000/500</td>
</tr>
<tr>
<td>26 - 35</td>
<td>23</td>
<td>46%</td>
<td>25</td>
<td>50%</td>
<td>1500/1000</td>
</tr>
<tr>
<td>36 - 45</td>
<td>16</td>
<td>32%</td>
<td>10</td>
<td>20%</td>
<td>2500/1750</td>
</tr>
<tr>
<td>46 - 55</td>
<td>3</td>
<td>6%</td>
<td>8</td>
<td>16%</td>
<td>3250/2500</td>
</tr>
<tr>
<td>&gt; 55</td>
<td>1</td>
<td>2%</td>
<td>1</td>
<td>2%</td>
<td>4000/3000</td>
</tr>
<tr>
<td>Totals</td>
<td>50</td>
<td>100%</td>
<td>50</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 shows that the majority of colonists selected by Mars One so far are between the ages of 26 and 35 while only 2 are in the highest radiation resistance category of over 55. The younger group has only 30 to 37.5% the radiation resistance of the older group.

99 Using current NASA standards, Buckey Space Physiology 2006
100 Extrapolated from NASA criteria for colonists less than 25 years of age
The radiation limit for males and females 25 and under is extrapolated from the NASA standards by taking the 500mSv difference between ages 25 and 35 for males and females and subtracting that from the limit for 25 and over for both groups.

The amount of time each of the above groups could spend on Mars building the colony before they would need to be in fully shielded habitats is illustrated below using the previous criteria of 324mSv exposure in route and 245mSv per year average exposure.

Table 7: Years of Unshielded Work Before Reaching Radiation Exposure Limits

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Radiation Limits for Males</th>
<th>Radiation Limits for Females</th>
<th>Years of Unshielded Work for Males</th>
<th>Years of Unshielded Work for Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 25</td>
<td>1000</td>
<td>500</td>
<td>2.76</td>
<td>0.72</td>
</tr>
<tr>
<td>25 - 34</td>
<td>1500</td>
<td>1000</td>
<td>4.80</td>
<td>2.76</td>
</tr>
<tr>
<td>35 - 44</td>
<td>2500</td>
<td>1750</td>
<td>8.88</td>
<td>5.82</td>
</tr>
<tr>
<td>45 - 54</td>
<td>3250</td>
<td>2500</td>
<td>11.94</td>
<td>8.88</td>
</tr>
<tr>
<td>&gt;= 55</td>
<td>4000</td>
<td>3000</td>
<td>15.00</td>
<td>10.92</td>
</tr>
</tbody>
</table>

The NASA career radiation exposure limits for those under the age of 26 are extrapolated from the respective difference between the limits for males and females age 25 to 34 which is subtracted from the limit for those over 25. The radiation exposure of the six-month voyage to Mars is subtracted from this limit. The remainder is then divided by the average annual expected radiation exposure to determine the number of unshielded years the colonist could work to establish shielded habitats, do exploration and research on the surface, or make repairs.
III. Methodology

The question of who to send as the first colonists to Mars or the Moon is very important to the success of these endeavors. One of the main threats to potential colonists is radiation. The colonists will experience a higher radiation exposure for a longer period of time than almost any human has ever experienced. What demographic factors should be considered in determining who is most resistant to the effects of radiation and who would have the longest period of productivity founding these colonies? To answer these questions objective standards of radiation exposure resistance were sought in the literature. The standards of several different space-faring agencies were discussed but the standards set by NASA for career radiation exposure limits for astronauts are adopted for this study. It was also necessary to determine the most likely average radiation exposure for each of these colonization sites and the voyage to them. Data from several sources was analyzed and collated for each site and average Apollo travel times and exposures to the Moon and expected travel times to Mars are calculated. The only time humans have left low Earth orbit was during the Apollo missions. This study assumes a 7-day voyage to the Moon and a 6-month voyage to Mars. It considers advanced radiation shielding methods but assumes current basic spacecraft shielding for the calculations. Potential colonists are evaluated by sex and age for radiation resistance, other factors such as race and personal genetics are discussed but not considered in the calculations. Radiation exposure from Hiroshima, Nagasaki and Chernobyl are considered and used to determine the morbidity and mortality expectations by age group only. The exposure from the voyage is subtracted from the NASA limits and the remainder is divided by the average radiation exposure expected per year to determine the expected allowable work period at these colony sites. The current colonist selection process used by the Mars One organization, the only organization currently selecting colonists, is
analyzed in light of the results of the above analysis. These calculations have been made for each group of potential colonist by age and sex to determine the optimal crew as related to radiation exposure limits and survivability. These calculations assume no advanced shielding technologies such as electromagnetic shielding or exotic metals. The resulting values are then used to determine the number of productive years the colonist could work on the surface, or in temporary unshielded habitats, to construct the underground or otherwise fully shielded habitats to house the colonists to come.

IV. Results

This paper has used the standards set by the United States for radiation exposure for different age groups working in high radiation environments and extrapolated from these standards for space travel to the Moon and Mars and yearly exposures for early colonization efforts. The amount of time these astronauts could spend on the surface to construct fully shielded living structures and bring the radiation level down to the Earth average has been calculated. Several nations have developed radiation cumulative exposure standards but we will use the standards set by the United States. The United States uses a sliding scale for radiation exposure based upon a person’s age and sex. Adjustments to individual exposure limits will need to be made on a continuing basis but this paper assumes the same level of exposure for all crew members, the need to adjust for solar storms, galactic cosmic radiation events, and individual exposure events, will be discussed but not factored into the equations as they are not predictable. Leukemia risk by age of exposure will be evaluated to illustrate the variation in relative risk by age group, see figure 8.
Age of Exposure

The age of a subject at the time of radiation exposure has a profound effect on increased mortality. Figure 8 compares the age of exposure with the subsequent loss of life expectancy from leukemia. This data was compiled by a joint US-Japan research foundation analyzing the after effects of the Hiroshima and Nagasaki nuclear detonations.¹⁰¹

Figure 8: Age of Exposure

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¹⁰¹ RERF Leukemia Risks Among Atomic Bomb Survivors 2000
The Moon

In the Apollo missions to the Moon a few millimeters of metal were all that stood between the crew and death, see table 8\textsuperscript{102}.

Table 8: Average Radiation Doses of the Flight Crews for the Apollo Missions\textsuperscript{103}

<table>
<thead>
<tr>
<th>Apollo Mission</th>
<th>Skin dose in rads</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.6mSv</td>
</tr>
<tr>
<td>8</td>
<td>1.6mSv</td>
</tr>
<tr>
<td>9</td>
<td>2.0mSv</td>
</tr>
<tr>
<td>10</td>
<td>4.8mSv</td>
</tr>
<tr>
<td>11</td>
<td>1.8mSv</td>
</tr>
<tr>
<td>12</td>
<td>5.8mSv</td>
</tr>
<tr>
<td>13</td>
<td>2.4mSv</td>
</tr>
<tr>
<td>14</td>
<td>11.4mSv</td>
</tr>
<tr>
<td>15</td>
<td>3.0mSv</td>
</tr>
</tbody>
</table>

Table 8 shows the radiation exposure during the Apollo missions ranged from 1.6mSv for Apollos 7 and 8 to 11.4mSv for Apollo 14. This shows a more than 7x variation depending on the mission. These disparities are the result of solar activity and fluctuations in solar and galactic radiation.

It is possible that during a long duration mission there will be a radiation event that will overcome almost any defense and be fatal to the crew. These extreme events are very rare and a smaller one accounts for the extreme radiation exposure of Apollo 14. If we take out this outlier the range is from 1.6mSv to 5.8mSv with a mean of 2.3mSv. A storm shelter for radiation events

\textsuperscript{102} McDivitt \textit{Apollo 14 Mission Report} 1971
\textsuperscript{103} English \textit{Apollo Experience Report – Protection Against Radiation} 1973
will be necessary in any long duration mission with current technology. The storm shelter should be in the center of the ship with all possible equipment and supplies arrayed around it to block radiation.\textsuperscript{104}

The Moon colonization recommendations have been calculated by taking the maximum career radiation exposure limits set by NASA by age and sex and subtracting the radiation exposure experienced traveling to the site and working in the open to build the shielded permanent habitats for the colonists that will come later. This paper assumes that the permanent habitats will be underground both on the Moon and, for later consideration, on Mars. There are several examples of underground cities, some capable of holding up to 20,000 people, in Turkey\textsuperscript{105} and China.\textsuperscript{106} If greenhouses are the only above ground feature it should be possible to limit the radiation exposure of these colonies to ambient levels equal to places on Earth so that those working outside in the greenhouses or exploring the surface limit their exposure to occupational health standards currently set by the National Regulatory Commission here on Earth.

NASA sets a career exposure limit for its astronauts by gender and age starting with a career total of 1500mSv for a 25yo male increasing to 2500mSv at age 35, 3250mSv at age 45 and 4000mSv at age 55. For a female the levels are 1000, 1750, 2500 and 3000 respectively. The following calculations use the NASA radiation exposure limits.\textsuperscript{107} These data will be analyzed in tables 9 and 10.

\begin{flushleft}
\textsuperscript{104} Johnson Space Center \textit{Spaceflight Radiation Health Program at JSC 2016}  \\
\textsuperscript{105} Pinkowski \textit{Massive Underground City Found in Cappadocia Region of Turkey 2015} \\
\textsuperscript{106} Anselm \textit{Earth Shelters; A Review of Energy Conservation Properties in Earth Sheltered Housing2016} \\
\textsuperscript{107} Buckey \textit{Space Physiology 2006}
\end{flushleft}
Table 9 shows that, for males, the oldest group of colonists considered will have 2.7x more productive years outside of full shielding than will the youngest. This means the youngest group will only have 37.3% as much useful unshielded surface work time. Even going up from age 25 to just 35 increases effective work years by 67%.

The increase in productive work time between the age groups is striking. On average there is an 833mSvt increase in career dose limit radiation tolerance and a 1.90 increase in years outside of shielding with each decade added to the base age. This analysis clearly shows a benefit to sending older male colonists to establish shielded habitats. In the lighter gravity the colonists would also be able to lift and move substantially heavier loads than on earth. There will be deconditioning during the Earth to Moon transit, despite exercise bands and other fitness equipment, but regular exercise and the weight of the spacesuits should provide adequate resistance once on the Moon to maintain strength.
Table 10: Years of Productive Unshielded Activity During Moon Colonization for Females\(^{108}\)

<table>
<thead>
<tr>
<th>Females by Age at Exposure</th>
<th>Career Dose Limit in millisieverts</th>
<th>Total Exposure Trip to the Moon</th>
<th>Yearly Exposure without shielding</th>
<th>Productive Years Outside of shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 25</td>
<td>1000</td>
<td>11</td>
<td>438</td>
<td>2.26</td>
</tr>
<tr>
<td>Age 35</td>
<td>1750</td>
<td>11</td>
<td>438</td>
<td>3.97</td>
</tr>
<tr>
<td>Age 45</td>
<td>2500</td>
<td>11</td>
<td>438</td>
<td>5.68</td>
</tr>
<tr>
<td>Age 55</td>
<td>3000</td>
<td>11</td>
<td>438</td>
<td>6.82</td>
</tr>
</tbody>
</table>

Table 10 shows that, for females, the oldest group of colonists considered will have 3.0x more productive years outside of full shielding than will the youngest. This means the youngest group will only have 33.1% as much useful unshielded surface work time. Going up from age 25 to just 35 increases effective work years by 60%.

The increase in productive work time between the female age groups is also considerable at 667mSv increase in career dose limit radiation tolerance and a 1.52 increase in years outside of shielding with each decade added to the base age. The analysis also clearly shows a benefit to sending older female colonists but further shows a significant increase in productive work years and radiation resistance for the male colonists compared to the female. This difference between the male and female radiation exposure limits was determined by an analysis of the increased cancer and mortality risks between men and women who were victims of the Hiroshima bombing. The data showed that women were more susceptible than men to radiation injury.\(^{109}\)

\(^{108}\) Buckey *Space Physiology* 2006

\(^{109}\) Kramer *Female Astronauts Face Discrimination from Space Radiation Concerns, Astronauts Say* 2013
Mars

This paper assumes a trip to Mars which results in 648mSv per year exposure with the shortest possible travel time and only current technology considered. This time period is six months. It is possible to reduce this time with advanced propulsion technologies like VASIMR or NERVA but these will not be considered. A six months long journey to Mars would give an exposure of 324mSv. The average exposure rate on the surface of Mars is 120mSv to 245mSv per year. The corresponding calculations are shown below considering the higher value.\textsuperscript{110}

Table 11: Productive Years for Males on Mars Calculated After Subtracting Voyage Exposure

<table>
<thead>
<tr>
<th>Males by Age at Exposure</th>
<th>Career Dose Limit in millisieverts</th>
<th>Total Exposure Trip to Mars</th>
<th>Yearly Exposure without shielding</th>
<th>Productive Years Outside of shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 25</td>
<td>1500</td>
<td>324</td>
<td>245</td>
<td>4.81</td>
</tr>
<tr>
<td>Age 35</td>
<td>1000</td>
<td>324</td>
<td>245</td>
<td>8.90</td>
</tr>
<tr>
<td>Age 45</td>
<td>1500</td>
<td>324</td>
<td>245</td>
<td>11.96</td>
</tr>
<tr>
<td>Age 55</td>
<td>3000</td>
<td>324</td>
<td>245</td>
<td>15.03</td>
</tr>
</tbody>
</table>

Table 11 shows that at age 55 a male colonist will have 3.1x more productive years outside shielding than the age 25 male group.\textsuperscript{110} Buckey Space Physiology 2006
Productive Years for Females on Mars Calculated After Subtracting Voyage Exposure

<table>
<thead>
<tr>
<th>Females by Age at Exposure</th>
<th>Career Dose Limit in millisieverts</th>
<th>Total Exposure Trip to Mars</th>
<th>Yearly Exposure without shielding</th>
<th>Productive Years Outside of shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 25</td>
<td>1000</td>
<td>324</td>
<td>245</td>
<td>2.76</td>
</tr>
<tr>
<td>Age 35</td>
<td>1750</td>
<td>324</td>
<td>245</td>
<td>5.83</td>
</tr>
<tr>
<td>Age 45</td>
<td>2500</td>
<td>324</td>
<td>245</td>
<td>8.90</td>
</tr>
<tr>
<td>Age 55</td>
<td>3000</td>
<td>324</td>
<td>245</td>
<td>10.94</td>
</tr>
</tbody>
</table>

Table 12 shows that at age 55 a female colonist will have almost 4.0x more productive years outside shielding than the age 25 female group.

These tables clearly show the advantage that an older colonist has to a younger one in radiation resistance. It is also important to note that while many people age 55 and over have had all the children they plan to, very few people age 25 would be likely to have done so. The radiation risks to the fetus of pregnant women is not analyzed here but having a pregnant female in an unshielded habitat would put the fetus at extreme danger of radiation injury including mutations and death.
Mars One Analysis

The Mars One organization is the only program that is actively selecting colonists for Mars. They plan a one-way trip with all selectees expected to stay the rest of their lives. It has recently selected 100 possible colonists for its planned mission.

They estimate the radiation exposure for 360 days at 662+/-108mSv which is close to our estimate of 648 per year of travel. They get this number from a study published in the journal Science in May 2013. They estimate a 210-day journey with an exposure of 386 +/- 63 which is again within our 6-month travel time estimate range of 324mSv exposure. They estimate a shielding level from the spacecraft walls of 10-15g/cm² with a dedicated radiation shelter with shielding of 40g/cm² in case of a Solar Particle Event (SPE). They expect one event every two months during the trip. They estimate the radiation level on Mars to be 30microSv per hour (0.03mSv). Which would give 262.8mSv per year. Again very close to, and actually higher than, our estimate of 245mSv. They report that five meters of Martian soil would provide 1,000g/cm² of shielding which would provide about the same protection as Earth’s atmosphere. They do not address possible radioactive elements in the soil or Radon gas accumulation in a completely sealed habitat. They estimate only 11mSv per year exposure from excursions outside the shielded habitat. This comes out to about sixty-one 12 hour shifts outside the habitat per year.

Mars One has provided a range of expected radiation exposures for both travel to and annually on Mars. I have collated these into a worst case and best case scenario which are summarized in tables 13 and 14 below.

---

111 Mars One How much radiation will settlers be exposed to? 2016
112 Mars One How much radiation will the settlers be exposed to? 2016
Table 13: Best Case Scenario

<table>
<thead>
<tr>
<th>Males / Age</th>
<th>Limit</th>
<th>Voyage</th>
<th>Yearly</th>
<th>Productive Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>1000</td>
<td>277</td>
<td>131</td>
<td>5.52</td>
</tr>
<tr>
<td>25</td>
<td>1500</td>
<td>277</td>
<td>131</td>
<td>9.31</td>
</tr>
<tr>
<td>35</td>
<td>2500</td>
<td>277</td>
<td>131</td>
<td>16.92</td>
</tr>
<tr>
<td>45</td>
<td>3250</td>
<td>277</td>
<td>131</td>
<td>22.65</td>
</tr>
<tr>
<td>55</td>
<td>4000</td>
<td>277</td>
<td>131</td>
<td>28.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Females / Age</th>
<th>Limit</th>
<th>Voyage</th>
<th>Yearly</th>
<th>Productive Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>500</td>
<td>277</td>
<td>131</td>
<td>1.7</td>
</tr>
<tr>
<td>25</td>
<td>1000</td>
<td>277</td>
<td>131</td>
<td>5.5</td>
</tr>
<tr>
<td>35</td>
<td>1750</td>
<td>277</td>
<td>131</td>
<td>11.21</td>
</tr>
<tr>
<td>45</td>
<td>2500</td>
<td>277</td>
<td>131</td>
<td>16.92</td>
</tr>
<tr>
<td>55</td>
<td>3000</td>
<td>277</td>
<td>131</td>
<td>20.72</td>
</tr>
</tbody>
</table>

Table 13 shows a best case scenario of 1.7 to 5.52 productive years on the surface for those 25 and younger and 20.72 to 28.33 for those at least 55 years old.

The best case scenario assumes no unusual energetic solar or galactic events causing increased radiation exposure. It assumes no extended space-walks or time outside the spacecraft, no increased radiation exposure from equipment or power generators on the spacecraft. It assumes a solar maximum (maximum shielding effect) exposure rate of galactic and solar radiation and no on-site radiation variables from elements in the soil. The worst case scenario will have the same assumptions except it will assume a solar minimum with higher resultant radiation levels only.
Table 14: Worst Case Scenario

<table>
<thead>
<tr>
<th>Male / Age</th>
<th>Limit</th>
<th>Voyage</th>
<th>Yearly</th>
<th>Productive Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>1000</td>
<td>385</td>
<td>263</td>
<td>2.34</td>
</tr>
<tr>
<td>25</td>
<td>1500</td>
<td>385</td>
<td>263</td>
<td>4.24</td>
</tr>
<tr>
<td>35</td>
<td>2500</td>
<td>385</td>
<td>263</td>
<td>8.04</td>
</tr>
<tr>
<td>45</td>
<td>3250</td>
<td>385</td>
<td>263</td>
<td>10.89</td>
</tr>
<tr>
<td>55</td>
<td>4000</td>
<td>385</td>
<td>263</td>
<td>13.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Female / Age</th>
<th>Limit</th>
<th>Voyage</th>
<th>Yearly</th>
<th>Productive Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>500</td>
<td>385</td>
<td>263</td>
<td>0.44</td>
</tr>
<tr>
<td>25</td>
<td>1000</td>
<td>385</td>
<td>263</td>
<td>2.34</td>
</tr>
<tr>
<td>35</td>
<td>1750</td>
<td>385</td>
<td>263</td>
<td>5.19</td>
</tr>
<tr>
<td>45</td>
<td>2500</td>
<td>385</td>
<td>263</td>
<td>8.04</td>
</tr>
<tr>
<td>55</td>
<td>3000</td>
<td>385</td>
<td>263</td>
<td>9.94</td>
</tr>
</tbody>
</table>

Table 14 shows a worst case scenario of 0.44 to 2.34 productive years on the surface for those 25 and younger and 9.94 to 13.75 for those at least 55 years old.

The above charts clearly show a severely restricted expected allowable work time outside a habitat shielded with five meters of soil. It also shows that the younger aged colonists would have a much more restricted ability to explore the Martian surface and make repairs. For further study most of this data can be found at “How much radiation will the settlers be exposed to?” by Mars One, [http://www.Mars-one.com/faq/health-and-ethics/how-much-radiation-will-the-settlers-be-exposed-to](http://www.Mars-one.com/faq/health-and-ethics/how-much-radiation-will-the-settlers-be-exposed-to).
Cancer and Mortality Increase

Understanding the increased risk of cancer and overall mortality are of significance in the colonist’s decision to travel to the site and establish the shielded habitats for the future general population. Demographic factors that reduce these risks are important to consider. A healthy diet including lots of fresh fruits and vegetables will contain nutrients that can repair some oxidative damage. Regular exercise, as noted, increases the body’s ability to withstand stress and repair damage. Despite the variability between individual’s resistance to radiation there are several studies that have quantified the average person’s ability to tolerate radiation over different periods of time. These data have been used to generate standards for long-term radiation exposure and the increased risk of cancer and risk of mortality. These standards are evaluated in tables 15 and 16.

Table 15 below shows the relative risk increase by sex and age.\textsuperscript{113}

Table 15: Increase in Cancer Risk by Acute and 10-year Radiation Exposure for Males\textsuperscript{114}

<table>
<thead>
<tr>
<th>Male</th>
<th>Normal Cancer Risk</th>
<th>% increase with 1Sv acute exposure</th>
<th>Normal Mortality Risk</th>
<th>% Increase with 1Sv/10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 25</td>
<td>34.9</td>
<td>3.10</td>
<td>18.5</td>
<td>1.99</td>
</tr>
<tr>
<td>Age 35</td>
<td>35.2</td>
<td>1.84</td>
<td>18.7</td>
<td>1.20</td>
</tr>
<tr>
<td>Age 45</td>
<td>35.5</td>
<td>1.38</td>
<td>18.9</td>
<td>0.92</td>
</tr>
<tr>
<td>Age 55</td>
<td>35.4</td>
<td>1.12</td>
<td>18.7</td>
<td>0.75</td>
</tr>
</tbody>
</table>

\textsuperscript{113}Clement Fundamentals of Space Medicine 2011

\textsuperscript{114}ibid

Table 15 shows that the increase in cancer risk by acute exposure in 25 year old males is 2.8x higher than that in the 55 year old age group. The mortality risk for 10 years at 1 Sievert is 2.7x higher.
Table 16: Increase in Cancer Risk by Acute and 10-year Radiation Exposure for Females\textsuperscript{115}

<table>
<thead>
<tr>
<th>Female</th>
<th>Normal Cancer Risk</th>
<th>% increase with 1Sv acute exposure</th>
<th>Normal Mortality Risk</th>
<th>% Increase with 1Sv/10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age 25</td>
<td>35.6</td>
<td>6.24</td>
<td>15.7</td>
<td>2.93</td>
</tr>
<tr>
<td>Age 35</td>
<td>35.2</td>
<td>3.50</td>
<td>15.5</td>
<td>1.70</td>
</tr>
<tr>
<td>Age 45</td>
<td>33.9</td>
<td>2.22</td>
<td>15.1</td>
<td>1.19</td>
</tr>
<tr>
<td>Age 55</td>
<td>30.8</td>
<td>1.73</td>
<td>13.9</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 16 shows that the increase in cancer risk by acute exposure in 25-year old females is 2.8x higher than those in the 55-year old age group while the 10 years at 1 Sievert risk is 2.7x higher.

It would seem clear from the above tables that using colonists over the age of 55 to establish the colony would give the least risk of cancer development and improve longevity chances. An all-male crew would have the longest productive work time but the psychological and social implications would have to be considered in the selection. The youngest group of colonists considered would have to knowingly accept a higher risk of cancer than the older colonists without considering the limits of radiation resistance.

\textsuperscript{115} Clement *Fundamentals of Space Medicine* 2011
V. Discussion

The best crew to send on the initial colonization missions to the Moon or Mars would be men and women over the age of 55 who have not worked in the nuclear industry or had extensive exposure to radiation. The colonization of the Moon has the advantage of being only seven days from Earth. This allows for an easy return in case someone has reached their exposure limit or some other emergency. Mars is much farther away and, while some colonists will choose to return, those traveling there to establish the colony should be willing to stay and make their lives there. In either case the research clearly indicates that in the selection of the optimal crew for pioneering colonization of the Moon or Mars several factors should be considered. The mission will require team members who are psychologically fit to work well with others in confined and stressful environments, who do not plan to have more children, who can tolerate isolation as well as separation from friends and family, and who will be least affected by the unavoidable radiation exposure that must be tolerated to establish and build the first shielded habitats that will allow later colonization by the general population. The recommendations drawn from the data suggests that a team of men over the the age of fifty-five, with no prior history of working in high radiation areas, would be best suited for these missions. Medications such as Zofran will be needed to combat the nausea and other effects of radiation poisoning so the crew can continue to safely operate the ship. Some medications and nutrients have a somewhat protective effect from radiation and should be available at all times. In cases of extreme radiation exposure, it will be important to rotate crew members in and out of the shelter when absolutely necessary to maintain ship and colony functions. Crewmembers with the highest resistance to radiation should have a proportionately longer exposure time to protect crewmembers at higher risk. The shelter should have the necessary equipment to control all critical systems as well as water and
food access. Trips from the shelter during high radiation levels should be limited to critical repairs only. There are nutrients and medications that can help make the cells more resistant but over time some loss is inevitable. Research in Alzheimer’s and other forms of dementia show that maintaining an active mental life can reduce the effects of these illnesses. It will be important to maintain entertainment and educational materials on-board to foster mental exercise and maintain acuity.

A selection of the most effective chemotherapy agents should be selected and stored on board in powder form to be rehydrated and used to treat cancers that develop. These agents would be targeted to the most likely cancers, skin cancers, leukemia and aplastic anemia etc. A doctor who is trained to perform minor surgeries and administer necessary medications will be a vital member of any colonization effort. Every member of the crew should undergo emergency medical technician training to supplement the doctor in case of mass casualty or incapacitation of the doctor. Positron Emission Tomography scanning would be very useful to evaluate for cancerous growths if the technology can be feasibly included on the mission. Palliative medications to alleviate pain would be necessary in the case of untreatable cancers or injuries. During high radiation events younger crew members would be admitted to the shelter first and would exit last so as to limit their exposure. The crew member with the lowest overall-cumulative exposure would be selected to carry out vital functions during high exposure events. The crew would be rotated by age and overall lowest cumulative exposure to reduce the risk to any individual colonist. The order of rotation would be predetermined before launch and adjusted frequently according to the exposure registered by each individual.

The evidence is clear that the most productive and cost effective way to establish colonies on the Moon and Mars should be to send men over the age of 55. These men should not be former
astronauts, pilots or from any other profession with a higher than normal exposure to radiation. Those meeting these criteria would be able to withstand the highest levels of radiation exposure for the longest periods of time. They should be willing to stay for several years, if not permanently, to construct the shielded habitats for the general population to come.

Mars One, the only organization currently selecting colonists for Mars has estimated the range of expected radiation exposure from a low of 554mSv per year of travel and 131mSv per year during solar maximum to a high of 770mSv per year of travel and 526mSv per year during solar minimum.

They are promoting the reasonable idea of using five meters of Martian soil to shield their habitats to a tolerable radiation exposure level. The difficulty of shoveling by hand, or with small equipment, and depositing this depth of soil over an entire habitat is not inconsiderable. While the gravity on Mars is considerably lower than that of Earth, and therefore humans will be able to lift more, the difficulty of moving this much material while wearing a full body spacesuit will still be very significant. The amount of time spent out in the open with no more shielding than a spacesuit will have to be considered for each colonist based on their individual radiation exposure limitations.
VI. Conclusions

The selection criteria on the Mars One website does not address previous radiation exposure. Of the 100 individuals selected 50 are males and 50 females. Of the males 7 are less than or equal to 25 years old, 23 are between 26 and 35, 16 are age 36 to 45, 3 are age 46 to 55 and only 1 is over 55 years old. The female candidates breakdown to 6 age 25 and less, 25 age 26 to 35, 10 age 36 to 45, 8 are 46 to 55 and 1 is older than 55. This means that only 2 of the 100 potential selectees would have the highest possible established radiation exposure limits. The evidence would indicate that the Mars One organization is making a grave error in their selection process by not considering the relative radiation exposure risk of the different age groups and sexes of their potential colonists. The youngest selected colonists could have only about 0.67 year (8 month) window of time to work outside before reaching their maximum allowed radiation exposure using the extrapolated NASA career standards with colonists in their 30s faring little better. Older colonists, age 55 and over, would have much more resistance to radiation exposure and could work in unshielded conditions for a much longer period of time. Mars One should consider modifying their selection process to account for this danger. Placing remote controlled heavy construction equipment on the Moon and Mars to be operated from the Earth for the Moon and from shielded habitats or orbit for Mars could be considered to allow for more rapid deployment of shielding materials to the necessary depth to protect colonists.
References


NASA. Why is space radiation an important concern for human spaceflight? Space Radiation Analysis Group, Johnson Space Center, 2014.


