Orbital Space Settlement Radiation Shielding

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Abstract

We examine the radiation shielding requirements for protecting the inhabitants of orbital space settlements. Following an extensive analysis of the literature, we recommend a limit of 20 mSv/yr for the general population and 6.6 mGy/yr for pregnant women based on the most relevant standards, existing data and background radiation on Earth. In a surprising result, radiation measurements on the International Space Station (ISS) and our calculations using OLTARIS, NASA's online radiation computational tool, indicate that space settlements in Equatorial Low Earth Orbit (ELEO) below about 500 km are likely to meet this standard with little or no dedicated radiation shielding. This reduces the mass of typical orbital space settlement designs by 95% or more, suggesting that the easiest place to build the first space settlements is in ELEO due to proximity to Earth and relatively low system mass.

It is important to note that there are significant uncertainties in our understanding of the human effects of the continuous low-level high-energy particle radiation characteristic of space in general and ELEO in particular that need to be resolved. Thus, our conclusions should be considered preliminary.

Acronyms

ELEO	Equatorial Low Earth Orbit
GCR	Galactic Cosmic Rays
High-LET	High Linear Energy Transfer, typically particles such as protons, nuclei, etc.
ICRP	International Commission on Radiological Protection
ISS	International Space Station
km	kilometer
KeV	Kilo (thousand) electron Volt
L5	Lagrange Point Five
LEO	Low Earth Orbit
LET	Linear Energy Transfer
Low-LET	Low Linear Energy Transfer, typically x-rays and gamma-rays
m	meter
MeV	Mega (million) electron Volt
mGy	milli-Gray, a measure of radiation

mSv	milli-Sievert, a measure of biological radiation damage
NCRP	National Council on Radiation Protection and Measurements
NEO	Near Earth Object
OLTARIS	web front end to NASA radiation codes
SPE	Solar Particle Events
T	metric ton (tonne)
u	number of neutrons and protons
yr	year

Introduction

Radiation levels in space are significantly higher than on Earth. Radiation can have a number of negative effects on the human body including but not limited to death, cancer, birth defects, cataracts and premature sterility [NCRP 1989][Fry 1996][NCRP 2000][Wrixon 2008][Straume 2010]. There is also limited evidence that radiation similar to that in space may cause cardiovascular and central nervous system problems. However, for settlements in ELEO or with adequate shielding acute effects such as death are essentially impossible and the primary concern is long term cancer risk.

Radiation risks to space settlers are likely to be a small fraction of other risks, such as launch accident, life support failures or depressurization; and radiation induced cancers are likely to be small fraction of all cancers. Less than 10% of the lifetime cancers in atomic bomb survivors subject to high radiation levels can be attributed to radiation [NCRP 2010 page 104] and there was no increase in cancer deaths below about 200 mGy exposure [NCRP 1993b page 20, 53]. This level is far higher than expected in space settlements because radiation levels can be reduced either by shielding materials or electromagnetic forces.

In this paper we examine the radiation protection requirements for permanent human settlements in orbit. It is well known that radiation in deep space, beyond Earth's magnetic field, is much greater than in LEO (Low Earth Orbit). Furthermore, careful examination of Figure 1 indicates that space settlements in Low Earth Orbit (LEO) that stay close to the equator will receive very little radiation compared to higher inclination orbits. This is because of the protective effect of the Earth's magnetic field. This effect is particularly strong for orbits near the equator as these orbits do not pass through the South Atlantic Anomaly (see Figure 1). Indeed, the light flashes experienced by the lunar Apollo astronauts and attributed to space radiation were not observed by Apollo astronauts in near-equatorial orbits below the radiation belts [NCRP 2006 page 192].

These observations lead us to a radically easier approach to establishing the first space settlements.

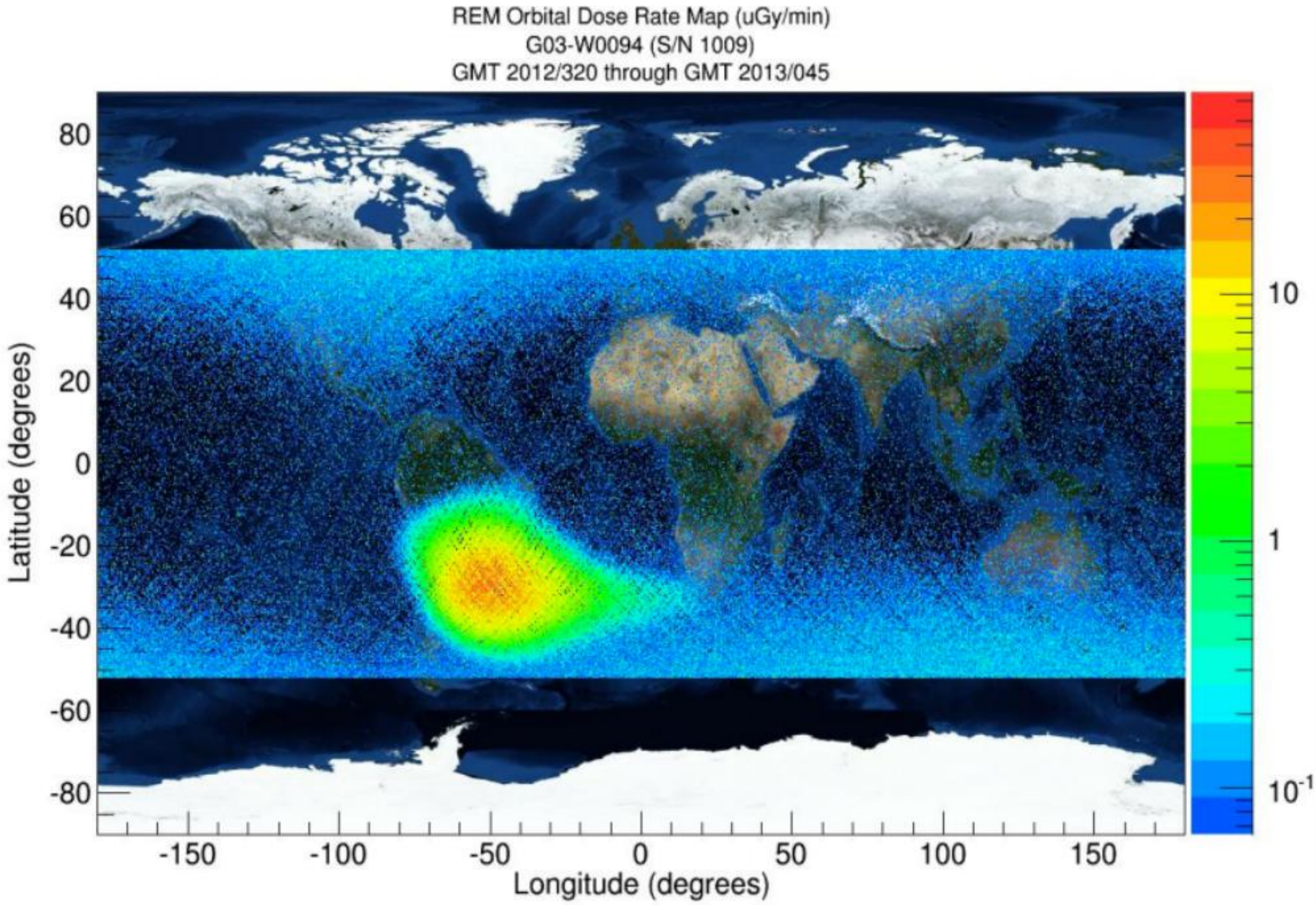

Figure 1: Radiation measurements taken on the ISS (International Space Station) at about 400 km altitude. Each dot is a color coded measurement. Note that most of the radiation is found above South America and the South Atlantic in a region known as the South Atlantic Anomaly. Here the proton flux above 50 MeV is increased ~1,000 times relative other locations at the same altitude [NCRP 2010 page 26]. Zero inclination orbits do not pass through this region and spacecraft in these orbits receive relatively little radiation. Image credit NASA.

By our definition a space settlement is a place where, among other things, children are raised, as opposed to a space station which is more of a work camp where people go for limited periods of time for specific purposes. This has important implications for radiation requirements as children, fetuses and embryos may be more susceptible to radiation damage than adults.

A series of studies in the 1970s [Johnson 1975][O'Neill 1977] suggested the feasibility of building large orbital space settlements suitable for permanent habitation. One of the system drivers was radiation, and the location chosen for settlement was the Earth-Moon L5 point[1] so that lunar materials could be used for radiation shielding. These studies assumed that lunar regolith radiation shielding with a mass equivalent to Earth's atmosphere above high altitude

[1] Earth-Moon L5 is a point on the lunar orbit equidistant from Earth and the Moon.

cities, roughly 4.5 tonnes per square meter of hull, would be sufficient to meet a 5 mSv/yr[2] limit for settlers at the Earth-Moon L5 point. The Sievert (sv) is a measure of radiation damage to tissue or material. This shielding mass is far more than the structural mass, atmosphere, and interior accommodations combined (a factor of 20 to 100 or more). An elaborate mining and transportation system was designed to deliver large quantities of lunar regolith to L5.

Unfortunately, the 4.5 tonnes per square meter of hull estimate is quite low. Our calculations suggest that to reduce radiation in deep space to our higher threshold of 20 mSv/yr for the general population and 6.6 mGy/yr for pregnant women requires 10-11 tonnes of lunar regolith per square meter, more than double the amount suggested by these early studies. The Grey (Gy) is a measure of radiation absorbed.

Fortunately, radiation shielding mass requirements can be substantially reduced by using better materials and/or by placing settlements in ELEO rather than above the Earth's magnetic field. Specifically, to meet the 20 mSv/yr and 6.6 mGy/yr limits our calculations suggest that 6-7 tonnes of water or polyethylene radiation shielding per square meter of hull is sufficient in deep space, such as at L5; and settlements in a circular 500 km ELEO may require little or no dedicated shielding, reducing settlement mass by a factor of 20-100 or more. If no dedicated radiation shielding is necessary, besides being far less massive and much closer, the first settlements do not need materials provided by extraterrestrial mining and processing. This suggests a smaller development step between large LEO space stations and hotels and the first settlements.

Since the 1970s there has been considerable improvement in our understanding of radiation in space and ways to reduce the impacts of that radiation, but most of the long term studies have focused on voyages to Mars, not settlement [e.g., Wilson 1997, Cucinotta 2012]. These studies have assumed a few years of exposure, minimal spacecraft mass as the vehicle must travel to Mars, and only adults on board. By contrast, settlement involves decades of exposure, the potential for significantly more radiation shielding mass as a settlement generally isn't changing orbit, and there may be children and pregnant women on board.

Radiation in Space

There are three major classes of dangerous radiation in space [Schimmerling 2014][ICRP 2012]:

The first class is caused by Solar Particle Events (SPE), also known as solar storms. SPE happen perhaps 5 to 10 times per year, except near a solar minimum when they occur less

[2] The modern measure of absorbed radiation is the Gray. The biological effect of a given level of radiation is measured in Sieverts. Conversion of Grays to Sieverts depends on the type of radiation involved and the tissue being exposed. mSv stands for milli-Sievert, or one thousandth of a Sievert. mGy stands for milli-Gray, or one thousandth of a Gray. When converting from mGy to mSv, the mSv figure is always larger than the mGy for the same location and dose. In parts of this paper this is apparently violated but not actually as Gy are measured at a point and Sv in a model of the female body in the calculations.

often [Cucinotta 2012]. The particles from SPE are directional, going outward from the Sun along magnetic field lines [Robbins 1996] in a relatively small area so most miss Earth entirely. SPE typically last for several hours to perhaps a day or so at peak exposure rates, and are dominated by protons with an energy of one MeV up to a few hundred MeV. SPE that do impact Earth primarily affect the polar regions as the Earth's magnetic field is more protective around the equator. In deep space, severe storms may require extra shielding for periods of a few hours to days or perhaps even weeks [NCRP 2000 page 38]. Fortunately, dangerously large SPE that impact Earth and its environs are rare and the Earth's magnetic field is usually protective.

The second class of dangerous radiation, and most important for space settlement, consists of galactic cosmic rays (GCR). Overall, GCR beyond the direct effects of the Sun is reported to be about 350 mSv/yr [NCRP 2010 page 27][3]. Dangerous GCR are made up primarily of nuclei with no electrons, can travel at relativistic speeds, and are omni-directional. The nuclear particles are 87% protons, 12% helium nuclei (alpha particles), and 1% heavier nuclei, with electrons and positrons only ~2% as common as the nuclear particles. Most of the dose is from protons, helium, carbon, neon, oxygen, silicon and iron [NCRP 2000 page 4]. Energy varies from less than one MeV/u[4] to more than 10,000 MeV/u with a median of perhaps 1,000 MeV/u. The level of GCR in the solar system varies with the solar cycle, with periods of low solar magnetic activity allowing more GCR into the inner solar system, but this effect is limited to energies less than roughly 2,000 MeV/u [Cucinotta 2012]. While most of the nuclei involved have low atomic number, the most dangerous GCR particles are probably heavy ions such as iron nuclei. However, such heavy particles may kill the cells in their path, which the body can easily clean up, while somewhat lighter particles may damage cells in ways that may be more difficult to repair [Marianne Sowa 2016]. Unlike most particles, a single heavy GCR particle can impact a number of cells [NCRP 1989 page 57]. Fortunately, GCR is at a fairly low level.

It is important to note that when a heavy particle typical of GCR passes through a material and strikes another nucleus, a shower of secondary particles is created in a process called spallation. These can be more damaging than the original particle, just as a shotgun wound can be more serious than a wound from a rifle bullet. Thus, a small amount of shielding can worsen radiation damage by creating secondaries, so shielding must be thick enough to absorb most of the secondaries as well as primaries.

There is a third class of space radiation which is relevant to settlements in Low Earth Orbit (LEO). This consists of electrons and protons trapped in the Earth's magnetic field [Schimmerling 2014] which can result in somewhat higher radiation levels in relatively low Earth orbit (very roughly 1,000 - 60,000 km). However, these are light, relatively low-energy particles (electrons and protons) that can be stopped by minimal shielding, such as a settlement hull. This radiation can cause problems for settlers performing spacewalks for repairs, construction or recreation.

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[3] Our calculations (see Table 2) suggest about 460 mSv/yr for all sources of radiation, not just GCR.
[4] MeV/u stands for million electron volts per neutron or proton.

Radiation in Low Earth Orbit (LEO)

Most of the known negative effects of radiation require relatively high doses, much higher than found in LEO, and there is not a lot of data for the low doses characteristic of that in LEO [NCRP 2000 page 69]. Altitude and orbital inclination determine the dose received in LEO [Fry 1996 page 34]. The lower the altitude the less the dose, and very small inclinations, near zero, receive much less radiation.

Under normal circumstances the Earth's magnetic field protects spacecraft in ELEO from most of the effects of SPE. For example, during a large flare in October of 1989 shuttle crews did not measure any increase in radiation, although there was a 30-40 mGy increase in the Mir space station, which was at a higher inclination. In general SPE effects are only measurable in spacecraft when at high latitudes [Robbins 1996 page 17]. In LEO even a large SPE poses relatively little risk unless the event is in conjunction with a large geomagnetic storm that allows solar particles into areas normally protected by the Earth's magnetic field. This happened in November 1960 and August 1972 [NCRP 2000 page 42]. While SPE are rare, it may be that settlements in LEO will require a solar storm shelter. As protons are fairly easy to stop, compared to GCR, this shelter should require a relatively modest level of shielding.

GCR is attenuated in ELEO due to the protection of the Earth's magnetic field and the Earth itself. The GCR that does get through consists primarily of the higher energy, more massive particles. Collisions with shielding material can produce the neutrons [Robbins 1996 page 18][NCRP 2006 page 137] that are found in LEO spacecraft. Measurements on Mir suggest that this is a potentially major source of radiation damage that is hard to quantify [NCRP 2000 page 4] but the current data are insufficient to estimate risk [NCRP 2006 page 137].

In LEO, depending on the altitude and state of the Earth's magnetic field, space settlements can encounter trapped protons (electrons are at much higher altitudes) [Robbins 1996 page 12]. Most protons in LEO exhibit energies of 6-500 MeV; neutrons 10 KeV to 2 MeV [NCRP 2000 page 70]. The protons, at least, are relatively easy to shield against.

Comparison of Earth and Space Radiation

Most of the radiation expected in space settlements is high-LET (linear energy transfer), generally consisting of radiation particles passing through a material and depositing a great deal of energy relatively quickly. Many radiation sources on Earth emit low-LET radiation such as x-rays and gamma rays dominated by photons, not particles. Earth background radiation is about 60% high-LET (primarily inhaled radon) and the rest low-LET [BEIR 2006]. The effects of low-LET on the human body are not necessarily similar to high LET, but most of the data is from low-LET sources such as nuclear bombs, medical radiation, and nuclear power plants. [BEIR 2006] is an excellent review of what is known about the biological effect of low level low-LET radiation and, in general, high-LET radiation tends to have greater effects than low-LET radiation [NCRP 2006 page 187].

The next section is a survey of radiation effects on the human body and biological systems relevant to space settlement. Most readers can skip this section and go straight to “Radiation Limits for Space Settlement” on page 12.

Radiation and the Human Body

There are two classes of radiation effects on the body: deterministic and stochastic. Short term acute deterministic effects, such as radiation sickness and damage to bone marrow, appear only at doses far above those characteristic of LEO [Fry 1996 page 35], with typical damage thresholds around 1,000 mSv or more in a short period of time [NCRP 1989 page 69] and lethality at 2,000-4,000 mGy [NCRP 1989 page 70]. While there is no doubt that at high doses radiation causes disease and death, at low levels the association between radiation exposure and disease is uncertain and if there is an association there may not be causality [BEIR 2006 page 133].

Cancer

Cancer can be caused by radiation. However, the most relevant data we have (for low rate, low dose low-LET radiation[5]) does not show an increase in human cancer rates. Nuclear industry workers exposed to low rate low dose low-LET radiation, in most studies[6], have substantially *lower* cancer mortality rates than the general population [BEIR 2006 page 194][NCRP 2006 page 136]. Medical workers exposed to chronic low levels of low-LET radiation appear to have no increased cancer risk [NCRP 2006 page 136], at least after 1950. Commercial flight crews, who are exposed to somewhat higher levels of high-LET (GCR) radiation during flight (0.01 mSv per 1,000 miles [BEIR 2006 page 3] or around 3 mSv/yr of occupational radiation [NCRP 2010 page 31]) do not seem to have increased cancer rates [NCRP 2006 page 136] and evidence for any adverse health effect is inconclusive [BEIR 2006 page 204]. Rates of leukemia and thyroid cancer were observed in Chernobyl cleanup workers [BEIR 2006 page 203] who were exposed to much higher dose rates.

However, radiation is well known to lead to life shortening in animals and this shortening is due to induced cancer [BEIR 2006 page 76][NCRP 1989 page 85]. Furthermore, for lifetime exposure further life shortening per unit of radiation has been observed [BEIR 2006 page 77]. Cancer, particularly leukemia (cancer of the blood forming organs), is the primary target of radiation standards for astronaut radiation exposure. Several studies have searched for excess cancer due to spaceflight radiation but none has been found so far [NCRP 2006 page 128].

While radiation exposure is associated with leukemia, not all studies have found an increase [NCRP 1989 page 109]. Unfortunately, there is insufficient data to estimate the risks of cancer from protons and heavy ions (e.g., GCR) [NCRP 2006 page 137].

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[5] The primary radiation of concern in space is low rate, low dose high-LET radiation, i.e., cosmic rays.
[6] Only 4 of 33 nuclear industry worker studies reported in [BEIR 2006 page 195-196] found cancer mortality increases.

At dose rates much higher than expected for space settlers, [BEIR 2006 page 145] reports additional mortality risk estimates due to 1,000 Sv (50 years of radiation at our limit) of radiation absorbed by atomic bomb survivors as a function of age at exposure. For those exposed at age 10 additional risk was estimated at 18-22%, those exposed at age 30, 9%, those exposed at age 50, 3%. Furthermore, there was a clear reduction in life expectancy with increasing dose among survivors [Beir 2006 page 153].

[BEIR 2006 page 8] reports that each 100 mSv of low-LET low dose rate radiation absorbed above background increases cancer risk by about 1 percentile, but this is incidence not mortality. Assuming a 66% cure rate [NCI 2016] the increase in mortality is 1 percentile every 15 years at our 20 mSv/yr limit.

To put the risks of space radiation-induced cancer in perspective, lifetime cancer risk on Earth today is 30-40% and the cancer caused death rate is about 20-25% [ICRP 2003][NCRP 2010 page 119].

Cataracts

Long term deterministic effects such as cataracts are of concern. Indeed, the only negative effect of space radiation on astronauts found so far is cataract formation [NCRP 2006 page 129]. The threshold for cataract formation is 2,000 mGy for (low-LET) x-rays [NCRP 2000 page 87][Fry 1996 page 44 and 238]. NCRP recommends limiting lifetime radiation exposure to less than 275 mSv for high-LET such as GCR to avoid cataracts [NCRP 1989]. It should be noted that 90 percent of the human population over 65 has some loss of lens opacity [NCRP 1989 page 89] and effective treatments are available.

Sterility

Radiation can cause sterility in both men and women, although men are more susceptible [NCRP 2000 page 104,138][Fry 1996 page 42]. There have been a number of studies of people exposed to radiation at work, e.g., nuclear power plant operators, that indicate a possible small effect on fertility in both men and women [Straube 1995, Doyle 2001].

Female Sterility

At levels below our limits there appears to be little chance of long term female infertility, which seems to require at least 1,000 Gy (150 years at a dose of 6.6 mGy/yr) or more [NCRP 1989 page 77]. Male and female mice irradiated with Co60 gamma rays at over 7,000 mGy/yr for ten generations had normal reproduction [NCRP 2000 page 104]. Table 5.6 in [NCRP 2000] suggests that below 600 mGy (90 years at 6.6 mGy/yr), radiotherapy to the ovaries has no negative effect. Based on medical radiation experience, [Herrman 1997] found that the mean tolerance for ovaries is between 5,000 and 10,000 mGy (775 - 1,500 years at 6.6 mGy/yr). However, there is some evidence that doses in LEO are high enough to reduce the number of primary oocytes and may have some long term effect on fertility [NCRP 2010 page 9].

Male Sterility

The testes are very sensitive to radiation [NCRP 2000 page 104][NCRP 1989 page 78]. However, our limit for adults and pregnant women are well below limits proposed for testes:

- The 380 mGy/yr annual dose limit to the testes recommended by the Radiobiology Advisory Panel, Committee on Space Medicine for astronauts. This limit assumes a somewhat older population [NCRP 2000 page 95].
- The 200 mGy (30 years at 6.6 mGy/yr) level suggested by Figure 5.11 in [NCRP 2000] for damage to the testes.
- The 50 mSv/yr limit in [NCRP 1989 table 5.3 page 79] based on a 400 mSv/yr threshold for temporary and 2,000 mSv/yr for permanent sterility when delivered over many years.

Relevant data include:

- [Herrman 1997] found that the mean tolerance for decreased sperm counts may require between 2,000-3,000 mGy (300-450 years at 6.6 mGy/yr).
- An acute dose of 150 mGy can cause a sperm count decrease of about 40% within a few months and 300 mGy can cause temporary sterility [Fry 1989 page 78].
- The temporary sterility threshold for a single absorbed dose is 150 mGy (22 years equivalent) [NCRP 2010 page 38].
- Under prolonged exposure the temporary threshold is 400 mGy [NCRP 2010 page 38].
- For temporary sterility the prolonged threshold is 2,000 mGy [NCRP 2010 page 38].
- For permanent sterility the single dose threshold is 3,500-6,000 mGy [NCRP 2010 page 38].

Unlike most tissue, for the testis spreading the dose out in time, characteristic of occupational and space settlement exposure, may increase damage to the testis rather than reduce it [NCRP 2000 page 103].

Heritable Effects

Fortunately, no radiation induced heritable effects have been demonstrated in humans [NCRP 2010 page 53]. There was no observed increase in cancer of the children of atomic bomb survivors [NCRP 1993b page 68] and no increase in stillborn children or various measures of inherited disease [NCRP 1993b page 91-92]. No adverse effects have been found in the children of atomic bomb survivors [BEIR 2006 page 9] and low or chronic doses pose little genetic risk compared to population baselines. An increase in leukemia in children whose fathers worked at a nuclear power plant in England and received radiation doses comparable to our limits was detected but the total numbers of cases was small and other epidemiological studies have found no effect [NCRP 1993b pages 68-69].

Central Nervous System

There has been concern for some time that GCR could affect the nervous system by damaging or killing nerve cells, but at levels far above our limits (20 mSv/yr and 6.6 mGy/yr). The effects of low-LET on the brain are fairly well known but in adults negative effects require doses of 2,000 mGy or more (300 years at 6.6 mGy/yr) [NCRP 2006 page 147]. Studies on rodents suggest that 200 Gy of iron ions (high-LET) may have an affect on the central nervous system [NCRP 2006 160]. 2,000 Gy of iron ions causes rats to perform more poorly in operant conditioning tasks and 1,500 Gy has caused negative effects on spatial learning and memory [NCRP 2006 page 161]. In vitro effects on nerve cells have been demonstrated at similar or higher radiation levels [NCRP 2006 pages 164-166]. All these levels are far above those experienced in LEO and current data do not appear to suggest that that radiation-induced early effects on the brain are a concern for space-flight crews [NCRP 2006 page 239].

Cardiovascular Disease

Data from atomic bomb survivors indicate that radiation can cause coronary heart disease [NCRP 2006 page 168]. People receiving 5,000 to 50,000 mGy of low-LET radiation (750-7,500 years at 6.6 mGy/yr) for medical treatments have increased cardiovascular disease [NCRP 2006 page 171]. This is also found in Chernobyl cleanup workers [NCRP 2006 page 171]. For Chernobyl workers there was statistically significant increased risk of cardiovascular disease above 150 mGy (23 years at 6. 6 mGy/yr) [NCRP 2006 page 172]. Atomic bomb survivors have experienced significant increases in inflammation which may lead to heart disease [NCRP 2006 page 173].

Data Source Limitations

Unfortunately, much of what we know about radiation effects on the human body comes from studies of the victims of the Hiroshima and Nagasaki atomic bomb attacks, involving very high radiation levels for short periods of time, which do not necessarily generalize to long term exposure to low level GCR [NCRP 2006 page 235]. Furthermore, there is a controversy over the size and nature of the biological effects of the low dose-rate radiation characteristic of GCR [NCRP 2000 page 107] and little data on human health effect [Fry 1996 page 33]. Indeed there are no human data on cancer or other effects induced by protons or heavier nuclei [NCRP 2000 page 115].

Many medical procedures involve irradiating patients and studies of these patients can provide valuable clues. Medical imaging procedures can deliver around 0.02-300 mGy per procedure and individuals will often be imaged many times in a lifetime [BEIR 2006 page 156]. Radiation used to cure disease typically involves much higher doses, up to 6,000 mGy. These doses are so high that the effect of treatment on nearby organs can sometimes be used to cast light on low dose effects, such as secondary cancers induced when radiation is used to treat a tumor. However, medical radiation is all low-LET (particularly x-rays) and dose rates are much higher than those expected for space settlers, making interpretation of the data difficult.

Data on chronic low-level exposure has been gathered in studies of occupational and environmental exposure. However, the effects of chronic low-level radiation are difficult to detect due to difficulty in getting accurate measures of the exposure, the small size of effects, and confounding factors [BEIR 2006]. The small size of the effects means that very large populations must be studied [BEIR 2006 page 138] which presents practical problems and high cost. Furthermore, occupational sources are primarily low-LET radiation although environmental exposure has a significant high-LET component, mostly from radon exposure (61% worldwide).

Radiation studies on animals can use high-LET radiation but are usually limited to short time periods because that is vastly easier to execute and costs much less. Short periods of high flux are used to model low levels for longer periods. However, there is evidence that data from high dose and high dose rate radiation will overestimate the risks for low dose and low dose rate radiation [BEIR 2006 page 77]. After all, one could not predict the effects of sunlight on human skin from studies where subjects were illuminated with a year's worth of solar optical and UV radiation in few hours.

We now present the data and thinking behind our 20 mSv/yr and 6.6 mGy/yu limits for space settlement residents. We then quantify expected radiation levels in various situations with OLTARIS, NASA's web front end to sophisticated radiation modelling software [OLTARIS 2011, OLTARIS 2014].

Radiation Limits for Space Settlement

The amount of shielding thought necessary to protect settlers from the space radiation environment depends heavily on the limit chosen. The limit depends on the amount of risk one is willing to bear, which is difficult to quantify and depends on a number of cultural factors which vary considerably from society to society. In general increased risk is perceived to be more acceptable for voluntary, highly beneficial activities that affect small numbers of people. All these are true of space settlers [Slovic 1996b], although the risk is not voluntary for children born on a space settlement. In any case, it should be kept in mind that the 'acceptable' amount of risk is a bit arbitrary and the data linking human exposure to space radiation and damage do not support particularly accurate prediction. Also, radiation risk to space settlers is likely to be a small fraction of other risks and radiation induced cancers are likely to be a fraction of all cancers.

We have chosen a 20 mSv/yr limit for the general population to match the most relevant existing practice (see next paragraph), and 6.6 mGy/yr for pregnant women to avoid known problems by a wide margin. This is well above the 5 mSv/yr used in the 1970s studies, which is, in our opinion, unnecessarily conservative. Our limits are well below the limit for deterministic radiation effects[7], 500-2,000 mGy (depending on the tissue) [ICRP 2012], and are intended to limit stochastic effects such as cancer. Excess deaths from cancer have only been

[7] A deterministic radiation effect is one that is almost certain, such as radiation sickness, as opposed to stochastic effects such as contracting cancer which are not certain but rather probabilistic.

demonstrated for high doses (around 200 mGy) [NCRP 2000 page 109], which would require 30 years of exposure at 6.6 mGy/yr.

We first examine the 20 mSv/yr limit for the general population followed by a discussion of the 6.6 mGy/yr limit for pregnant women and other issues. These limits are comparable to current ICRP (International Commission on Radiological Protection) and NCRP (National Council on Radiation Protection and Measurements) occupational limits, but are much higher than limits for the general population. However, radiation limits in current usage are not ironclad but are rather adapted to situations as they arise. For example, [NCRP 1993a page 42] "... recommends that consideration be given to establishing special dose limits for those selected occupational groups requiring higher exposures to accomplish needed activities." That same publication on page 49 permits much higher levels of radon than one might otherwise expect because "... remedial action ... at this value could involve a very large number of homes and great societal cost."

Radiation Limit for the General Population (20 mSv/yr)

Relevant standard limits to consider include:

- The ICRP recommends a 20 mSv/yr limit for occupational radiation exposure [Wrixon 2008].
- The NCRP recommends no more than 50 mSv/yr for radiation workers in the U.S. [Space Radiation Analysis Group 2014][Fry 1989 page 161] with a '10 mSv x age' lifetime limit [NCRP 1993a table 1.1 and page 34] [NCRP 1989 page 156].
- The NCRP recommends no more than 1 mSv/yr average for the general population plus 5 mSv/yr for infrequent exposure [NCRP 1993a Table 1.1 and page 46].
- U.S. federal law mandates occupational exposure be less than 50 mSv/yr [NCRP 2010 page 15].
- The NCRP recommends 10 year limits for professional astronauts that varies from 40-300 mSv/yr depending on age and gender [NCRP 2000 page 143 table 6.2].
- The annual limit for US astronauts is 500 mSv/yr in the blood forming organs with a lifetime cap of 10,000 - 30,000 mSv for women and a higher limit for men [Space Radiation Analysis Group 2014].

It should be noted that these limits are all for man-made radiation and do not include background radiation or medical exposure. They are also somewhat inconsistent. On this basis, one could recommend a limit anywhere between 10 and 50 mSv/yr. This is not surprising given the limited data and varying assessment of risk, and we choose 20 mSv/yr.

20 mSv/yr is considerably above the average background radiation, which is 3.1 mSv/yr in the U.S. [Linnea 2010, NRC 2010] and 2.4 mSv/yr globally, 61% high-LET (mostly inhalation of radon) and 39% low-LET. However, these are averages, and much higher levels exist locally. Globally background radiation is generally in the 1-10 mSv/yr range [BEIR 2006 page 30], but there are several large regions of Europe, particularly in Spain and Finland, with levels over 10

mSv/yr [World Nuclear Association 2014] and there are inhabited parts of the world with much higher levels with no known major negative effects [BEIR 2006].

Extremely high background radiation areas include Yangjiang, China, Kerala, India, and Guarapari, Brazil. The highest recorded background radiation on Earth are in Ramsar, Iran, where monitored individuals have received an annual dose of up to 132 mGy/yr [Ghiassi-nej 2002]. The background radiation in parts of Kerala, India are as high as 70 mGy/yr where an extensive ten year study of 69,958 residents over 30 years old found elevated unstable chromosome aberrations but no excess cancer risk in areas of high background radiation [Nair 2009]. A 16-year study of about 30,000 subjects including children in Yangjiang, China found no statistically significant relationship between background radiation levels and cancer or cancer deaths [Tao 2000]. [BEIR 2006 page 228] summarizes four studies of high background radiation areas and found little or no increase in disease rates in high background radiation levels compared to lower areas.

Traditionally, the U.S. space program has sought to limit increased fatal cancer risk to three percentile for astronauts as this was about the lifetime frequency of occupational mortality in moderately risky professions when this standard was adopted [Sinclair 1996 page 51] [Slovic 1996a page 3]. Using the probability of radiation-induced cancer deaths from [NCRP 1993a Table 7.1], fifty years of living in a space settlement receiving 20 mSv/yr (1,000 mSv total) would increase cancer risk 5 percentile (e.g., from 25% to 30%) given the cancer treatment of the time. Table 13.5 in [NCRP 1993b] suggests that the increased probability of fatal cancer in ages 0-90 is 8.7 percentile using somewhat different assumptions. Severe genetic effects would be expected to increase by 1.3 points with the same assumptions [NCRP 1993a table 7.1]. In 2007 NASA estimated that this should limit exposure on a one year mission to 520 mSv (26 years at 20 mSv/yr) for a 25 year old male and 370 mSv (18.5 years at 20 mSv/yr) for a 25 year old female [NCRP 2010 page 98 table 6.1]. Limits are higher for older astronauts.

[BEIR 2006 page 8] estimates a 1 percentile increase in cancer incidence per 100 mSv received in the form of low-LET low dose rate radiation above background, meaning that 50 years in a space settlement with a 20 mSv/yr limit might increase cancer incidence (not fatality) by 10 percentile. Assuming a 66% cure rate [NCI 2016] the fatality rate might be increased by as much as 3.3 percentile, which is roughly consistent with the U.S. astronaut risk guidelines for adults moving to a settlement but not for children who may spend a lifetime in orbit.

As the first space settlement construction projects will almost certainly not begin for two or three decades and construction may easily take another decade, there is perhaps 30-40 years of improvements to cancer treatment before any settlers are exposed to space radiation. Even then, while radiation-induced leukemia risk increases a few years after exposure, solid tumor risk increases one to two decades later [NCRP 2010 pages 75,76]. From 2003-2012 cancer fatalities in the U.S. dropped 1.8% per year for men and 1.4% per year for women [NCI 2016] in spite of increased cancer rates. If survival rates continue to improve at this pace cancer deaths overall for ELEO space settlers could well be much less than on Earth today.

In the small, self-contained environment of a space settlement there are a few factors that may reduce cancer risks:

- It may be possible to limit or even ban chemical carcinogen and mutagen use in settlements.
- There will not be any radon inhalation, which causes about 20,000 radiation related deaths per year in the U.S. [Radon 2016].
- Smoking will almost certainly be banned. Smoking is a major cause of cancer.
- Food production efficiency may mandate a near-vegan diet, which has been associated with lower cancer risk [Greger 2015]. Certain foods have been shown to be radioprotective; for example, strawberry extract [NCRP 2006 page 163] and dietary vitamin-A acetate [NCRP 2006 page 144].
- There is evidence that some people are genetically more or less prone to radiation effects [NCRP 2006 page 133] [BEIR 2006 page 14], and space settlers could be screened on this basis.

Thus, it seems that 20 mSv/yr is a reasonable limit to use for the present study, being aware that additional research is needed and this limit may need to be changed as better data and theory become available. However, this is for the general population and certain subpopulations may require greater protection, particularly pregnant women.

Radiation Limit for Pregnancy (6.6 mGy/yr)

There is reason to believe that the radiation limit should be lower for the embryo and fetus. We have chosen 5 mGy/pregnancy (6.6 mGy/yr) primarily based on data and recommendations found in ICRP and NCRP publications.

The ICRP has developed guidelines for acceptable radiation levels for (among other things) the embryo and fetus. An ICRP publication [Wrixon 2008] established radiation thresholds based on [ICRP 2000] and [ICRP 2003] for various radiation threats to the fetus and embryo and included the following values as indicating the dose at which problems have been observed:

Effect	mGy threshold
Pre-implantation lethality	100
Introduction of malformations	100
Severe mental retardation	300
Negative effects on IQ	100
Life-time cancer risk increase	100

Table 1. Data from [Wrixon 2008]. The rows list possible effects of radiation exposure before birth. The numbers are a summary of radiation thresholds for pregnant women as part of

recommendations for radiation dose, which is relevant to medical decisions for pregnant women (e.g., whether to have an x-ray or not).

Notice that the values given here are in mGy, a measure of radiation absorption, not mSv, a measure of biological effect. This is because there is presently no meaningful way to judge the correctness of the tissue-weighting factors used to convert radiation (in mGy) to biological effect (in mSv) [ICRP 2003] for the fetus or embryo. For example, the effect of a given dose of radiation on the fetus depends greatly on when it occurs [ICRP 2003].

It should be noted that [NCRP 1993a page 38] recommends an occupational dose limit of 4.5 mSv/pregnancy (0.5 mSv per month) to protect the embryo and fetus, excluding background and medical radiation. This is slightly less than our 5 mGy/pregnancy (6.6 mGy/yr), assuming a conversion factor of 1 (corresponding to low-LET radiation), but when average background is added (3.1 mSv/yr in the U.S.) our limit is actually slightly lower. This does not consider that in orbit most of the radiation is high-LET GCR which may have quite different effects and a conversion factor greater than 1.

As the effects of radiation during pregnancy is a complex subject, we have abstracted the most relevant sections of the ICRP pregnancy-related publications [ICRP 2000] and [ICRP 2003] for readers who would like a more detailed examination:

- Many effects of prenatal radiation do not manifest with less than 100 mGy exposure, although a few show up at 50 mGy [ICRP 2003].
- [Wrixon 2008] recommends a 1 mSv/pregnancy limit for women with occupational radiation exposure and [ICRP 2000] recommends 1 mGy/pregnancy. This is in addition to the background radiation, which, as noted above, can be much higher than than 5.6 mGy/yr (which would bring the total to our 6.6 mGy/yr limit) in many places on Earth.
- The U.S. Nuclear Regulatory Commission recommends no more than 5 mSv (above background) of occupational exposure per pregnancy [NRC 1999].
- [ICRP 2003] notes one study suggesting that 10 mGy of medical radiation[8] to the fetus may result in an additional child cancer death for each 1,700 fetuses exposed (in addition to the 4-5 one would otherwise expect). However, other studies suggest that the childhood cancer rate due to 10 mGy would be less than this.
- [ICRP 2003 Table 4] indicates that fetal absorbed dose below 5 mGy per pregnancy shows no increase in childhood cancer or increase in malformations. However, a dose of 10 mGy/pregnancy has a slightly higher risk of childhood cancer.
- Nuclear bomb victims in utero showed sharp increases in severe mental retardation with doses >= 200 mGy when 8-15 weeks pregnant and >=600 mGy for 16-25 weeks, but not below these thresholds or at other points in pregnancy [ICRP 2003 Figure 5.1].
- “There were 10 cancer deaths among 1,078 prenatally exposed people in Hiroshima and Nagasaki…. The 807 people with estimable in-utero doses of at least 10 mSv included eight cancer deaths…” at ages 0-46 years. [ICRP 2003 paragraph 376].

[8] In cases where the mother needs radiation-based diagnostics or treatment.

- 100 mGy or less can cause pre-implantation death during some radiosensitive stages [Valentien 2003 paragraph 409].
- In a very large study[9] of children whose mothers were x-rayed during pregnancy it was found that there were 200-640 excess cancer deaths per 10,000 people per 1,000 mGy ages 0-16. The corresponding figure for atomic bomb victims was 70 [ICRP 2003 paragraph 397]. If there is no threshold, and the effect is linear to zero, that would imply 0.35-3.2 additional cancer deaths per 10,000 at 5 mGy exposure if spreading out the dose does not reduce effects.
- The ICRP does not recommend pregnancy termination at fetal exposures less than 100 mGy from medical sources [ICRP 2000].
- There is evidence that cyclotron neutrons cause more cancers than x-rays and gamma-rays, the radiation used in most of the studies referenced in [ICRP 2003 paragraph 280]. There is essentially no data for low-level GCR effects during human pregnancy.
- Most of the data available are for short periods of high radiation (atomic bombing, medical x-rays) and there are many experiments with rodents showing that negative effects are reduced if the same amount of radiation is delivered over a protracted time period [ICRP 2003 paragraph 424], which would be the case for space settlers.

Note that on Earth there is a 15% spontaneous abortion rate, 2-4% chance of major malformations, a 4% chance of retardation and 8-10% chance of genetic disease [ICRP 2003].

We believe that it might be wise to keep prenatal exposure to significantly less than 100 mGy over nine months and that 5 mGy per nine month pregnancy may be a good limit, which translates to about 6.6 mGy/yr. This is 20 x less than the threshold for considering pregnancy termination and is the highest level with no reported increase in childhood cancer in [ICRP 2003 Table 4].

It should be noted that the NCRP recommends that female astronauts not fly while pregnant since they can be scheduled for missions at other times [NCRP 2000 page 145]. This is not an option for settlers as they, by definition, live in space permanently.

Radiation Limit for Children

We have chosen not to have a separate radiation limit for children, even though the ICRP reports that radiation-introduced carcinogenesis is low for adults, low to medium for fetus and embryo and high for children [ICRP 2015 paragraph 132]. Susceptibility to radiation-induced cancer is strongly associated with exposure age [NCRP 2010 page 74] but the direction of susceptibility depends on the cancer involved, and overall cancer risk for a given radiation load is usually somewhat greater for children than adults. However, as mentioned above, a large 16-year study including children in the high background radiation area of Yangjiang, China found no statistically significant relationship between background radiation levels and cancer or cancer deaths [Tao 2000]. Studies of populations near the Chernobyl nuclear power plant after the

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[9] The Oxford Survey of Childhood Cancers, aka OSCC [Gilman 1988]. Note that this survey had some methodological problems, such as depending on the mother's memories for x-ray history.

accident appear to show no increase in childhood leukemia [BEIR 2006 page 227], although thyroid cancer increased [BEIR 2006 page 228] in highly contaminated areas.

[UNSCEAR 2013 paragraph 47f] states that "...the Committee recommends that generalizations on the risk of effects of radiation exposure during childhood should be avoided" due the complexity of effects depending on the details of exposure. Note that none of the data behind the differential between adults and children is based on human exposure to continuous low levels of high-LET radiation (e.g., GCR), the primary threat for space settlement, but rather short periods of intense low-LET radiation from medical or nuclear bomb exposure data. Available data on long term low-level radiation suggest no increased cancer risk.

[UNSCEAR 2013 paragraph 47a] estimates that for a given radiation dose, children's lifetime cancer risk might be 2-3 times greater than for people of all ages but this is "uncertain." [UNSCEAR paragraph 47e] goes on to note that for a given radiation dose cancer risk is more or less common between children and adults depending on, for example, the organ affected. For 25% of organs cancer risk is higher for children, for 10% of organs cancer risk is lower, with the remainder being the same or the data inconclusive [UNSCEAR 2013 paragraph 47c]. [ICRP 2015 paragraph 96] notes that the excess absolute risk is rather low as children have a very low cancer rate in the first place. Indeed, for the first 25 years after exposure, cancer risk for children at a given radiation level is often less than for adults [UNSCEAR 2014 paragraph 80], although the risk extends for longer periods because children are younger and have longer remaining lifetimes. Finally, [ICRP 2015 paragraph 47d] notes that "projections of lifetime risk for specific cancer types following exposure at young ages are statistically insufficient."

Between 1972 and 2012 the five-year survival rate for U.S.childhood cancer has gone from about 10% to 84% [CureSearch 2016] while the incidence of childhood cancer has increased about 28% [CureSearch 2016]. From 2003-2012 childhood cancer fatalities dropped by 2% per year [NCI 2016] in spite of increased rates of cancer. If treatment continues to improve at this rate cancer deaths overall for children in space settlements in the mid 2000s could well be less than for children on Earth today.

In addition to meeting the proposed 20 mSv/yr for the general population and 5 mGy/yr per pregnancy, space settlement design should adhere to the ALARA (As Low As Reasonably Achievable) philosophy [Sinclair 1996 page 59] to reduce radiation absorption below the limits where practical.

Clearly, people moving from Earth to a space settlement can expect to be exposed to negative effects due to higher levels of radiation, but this can also be true for people moving from place to place on Earth. In addition, medical scanners can add 30-70 mSv per procedure and radiation treatment can deliver up to 4,000 mGy to the skin [NCRP 2010 page 31]. Also, consider that air travel exposes passengers and crew to elevated radiation levels due to GRC as there is less atmospheric shielding at high altitudes. In short, there are many ways in which we currently and willingly increase our radiation exposure in order to gain in other ways. This will be the case for space settlers as well.

We now turn our attention to protecting space settlers from the effects of space radiation, including calculations to quantify the radiation that settlers are exposed to as a function of settlement location and shielding.

Radiation Shielding Materials

The best shielding materials for space radiation, particularly GCR, are dominated by hydrogen. This is because heavy positively charged particles with a lot of energy are stopped primarily by electromagnetic interaction with electrons rather than collisions with nuclei [Ziegler 1988]. Indeed, collisions with shielding nuclei can increase effective radiation dose due to the creation of secondary particles. As a particle passes through good-quality shielding, large numbers of electrons are pulled out of position, transferring energy from the particle and eventually bringing it to rest. Liquid hydrogen might be the ideal shielding material from this perspective, but it is difficult to handle and maintain. Among the best practical materials are polyethylene and water [Wilson 1997].

Polyethylene consists of long strands of carbon atoms each bonded to two hydrogen atoms (except at the ends, which have three). It is a little better than water because carbon nuclei are smaller than oxygen, making for fewer collisions and less mass for about the same number of hydrogen atoms. Note that many asteroids are rich in carbon compounds and water.

We now present the results of several numerical simulations of radiation levels as a function of orbital location and shielding mass. All calculations use OLTARIS [OLTARIS 2011] [OLTARIS 2014], NASA's freely available web front end for sophisticated radiation codes.

Lunar regolith, which has little hydrogen, is a poor radiation shielding material. This is illustrated by the results of radiation simulations in Table 2 which shows the radiation level expected in "free space" (above the Earth's magnetic field in OLTARIS terminology), given the mass of the shielding and the type of material. Note that a much greater mass of lunar regolith is necessary to bring radiation levels below 20 mSv/yr than with polyethylene or water.

	polyethylene		water		lunar regolith	
tonnes/ m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	462	128	462	128	462	128
1	194	85	200	86	281	110
2	137	52	147	54	275	82
3	91	31	101	34	240	62
4	57	18.5	67	21	194	48
5	35	10.9	43	12.5	149	37
6	21.0	6.3	26.5	7.5	109	28
7	12.3	3.6	16.1	4.4	77	20.9
8					52	15.1
9					34.9	10.5
10					22.8	7.1
11					14.5	4.7

Table 2: Comparison of shielding materials in free space. The rows indicate yearly radiation levels at a given shielding mass except the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). The first column lists tonnes of shielding per square meter; the other columns list different materials and measures. The mGy columns are a (computational) dose absorbed at a point inside the shielding, and the mSv columns are effective dose equivalent which is a measure of biological damage across the whole body computed on a model of the female body inside shielding. The red color indicates that values are less than 20 mSv/yr or 6.6 mGy/yr. Note that polyethylene is a bit more effective than water, and both are quite a bit more effective than lunar regolith. All values are calculated by OLTARIS.

Space Radiation as a Function of TIme

The amount of radiation experienced in space varies with time, in great part due to the magnetic activity of the Sun, and OLTARIS simulates this effect. The less solar magnetic activity, the stronger the GCR in Earth orbit as the Sun's magnetic field deflects incoming charged particles. There is about a factor of three difference in the space radiation between solar minima and maxima [Robbins 1996 page 8]. All of the data presented here were calculated for a low solar activity period from 17 June 1977 to 17 June 1978 and are thus conservative. However, there are even lower radiation times, such as 17 June 2008 to 17 June 2009. For adults only the average dose over many years is relevant. However, for fetus and embryo only the 9 months while pregnant matter so exceptionally high periods of radiation could be a problem suggesting that planned pregnancies be timed to avoid solar minima.

Location Influence on Radiation Shielding Requirement

The radiation experienced by space settlers depends a great deal on location. In particular, radiation levels in LEO below the van Allen belts are much lower than in the rest of the solar system. Radiation levels in LEO are influenced by both the altitude of the orbit and the inclination. The lower a settlement is the more radiation protection it receives both from the Earth itself and from Earth's magnetic field. Very low inclinations, i.e., very close to 0, experience much less radiation due to the shape of the magnetic field. See Table 5 below.

On the surface of Mars or the Moon approximately 50% of the GCR is blocked by thousands of km of rock[10]. Thus, Table 2 can be used to determine rough radiation shielding requirements for surface settlements, ignoring SPE. Levels in the table below 40 mSv/yr and 13 mGr/yr meet our limits for surface settlements, which works out to roughly two tonnes less material per square meter.

Surface settlements can be located in caves or buried with local materials which are plentiful. Local materials can also be used by orbital space settlements when built co-orbiting with asteroids.

Radiation in Equatorial LEO

Table 3 contains the yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for zero inclination circular equatorial orbits as a function of polyethylene shielding measured in tonnes of material per square meter of hull. The shielding required to meet these limits increases with altitude as the Earth blocks less of the sky and the magnetic field weakens.

[10] Also, on Mars there is some protection from the atmosphere, although not much.

	600 km		700 km		800 km		900 km		1000 km	
tonnes/ m^2	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy
~0	40.1	1,559	494	12,400	2,364	30,620	398	55,090	10,160	99,410
1	14.0	5.2	25	10.6	113	61	247	135	425	235
2	14.1	4.9	18.3	5.9	39.3	9.8	72	15.8	116	23.7
3	12.2	4.1	14.5	4.7	23.4	6.4	37	9.0	55	12.4
4	9.6	3.2	10.9	3.6	14.8	4.3	21	5.4	29	7.0
5	7.0	2.3	7.8	2.5	9.5	2.8	12.0	3.3	15.7	4.1

Table 3: Yearly radiation levels calculated at five orbital altitudes for circular equatorial orbits in both mSv/yr (effective dose equivalent for a model of a female body) and mGy/yr (dose at a point). Rows are levels calculated for polyethylene shielding in tonnes per square meter of settlement hull with the exception of the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets our 20 mSv/yr or 6.6 mGy/yr limits. Note that at 0 shielding the dose (Gy) is higher than the effective dose equivalent (Sv). This is because the dose is at a point with no shielding and the effective dose equivalent is averaged over the whole body which self shields from easily stopped low energy trapped protons. All calculations use OLTARIS.

Noting that at 600 km with a single ton of shielding the radiation expected, 14.0 mSv/yr, is well under the 20 mSv/yr limit, we did additional calculations at 500 and 600 km using very small amounts of shielding. The results are in Table 4:

shielding	500 km		600 km	
tonnes/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	17.7	10.2	40.1	1,559
0.01	17.1	3.6	29.8	101
0.025	16.4	3.7	24.4	50.6
0.05	15.3	3.9	19.8	21.8
0.075	14.4	4.0	17.4	12.5
0.1	13.7	4.0	15.9	8.9
0.15	12.7	4.1	14.1	6.1
0.2	12.0	4.2	13.1	5.3
0.25	11.7	4.3	12.6	4.9
0.5	11.9	4.6	12.6	4.9
0.75	12.7	4.8	13.4	5.1
1	13.3	4.9	14.7	5.2
1.25	13.6	5.0	14.3	5.2
1.5	13.8	4.9	14.4	5.2
1.75	13.7	4.8	14.4	5.1
2	13.5	4.7	14.1	4.9

Table 4: Yearly radiation levels calculated for circular equatorial orbits at 500 and 600 km altitude. The rows are tonnes of polyethylene shielding with the exception of the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot

calculate zero shielding levels). The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets the 20 mSv/yr limit or the 6.6 mGy/yr limit for pregnant women. All calculations by OLTARIS.

Table 4 suggests that for settlements in low equatorial orbit (below 500 km), no shielding mass is required to meet the 20 mSv/yr and only a tiny amount (equivalent to 0.01 ton/m^2 of polyethylene) to meet the 6.6 mGy/yr limit. The ISS has about an average equivalent of 0.2 tonne/m^2 aluminum shielding [Cucinotta 2013], including interior furnishings. Thus the minimal shielding provided by a pressure hull, solar arrays, whipple shield, etc. should be sufficient to meet the pregnant woman threshold. This has radical implications for space settlement as discussed below.

Note that there is a very high radiation level (mGy/yr column) with no shielding at 600 km. This is mostly trapped protons that can be easily shielded as is seen from the rapid drop-off when small amounts of shielding are added.

Figure 2 illustrates the physics behind this effect.

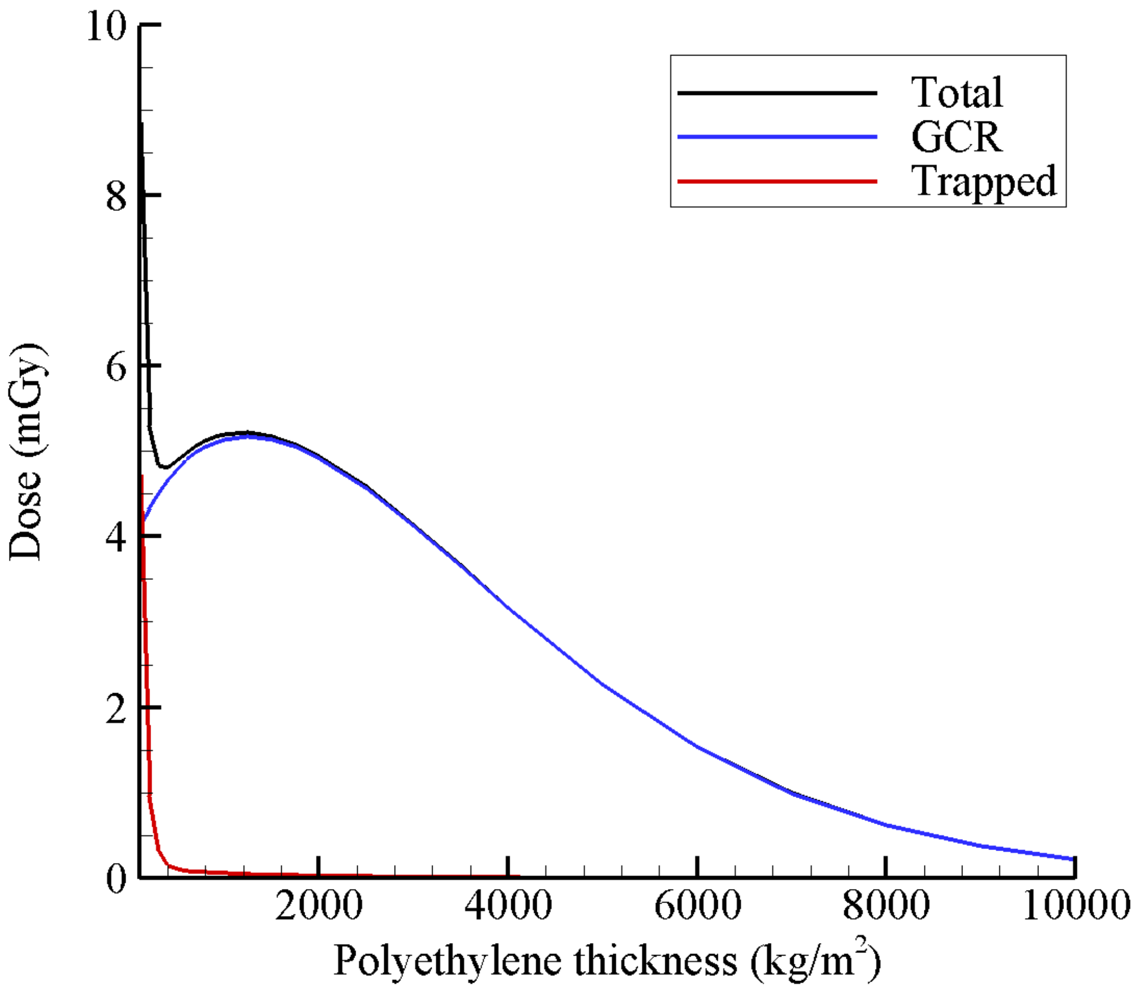


Figure 2: Radiation for a circular orbit at 600 km and 0 degree inclination. The trapped proton component (red line on plot) consists mainly of lower energy protons that are stopped with little shielding. The dose profile falls off rapidly with depth as one might expect. Image credit NASA.

The GCR component (blue line on plot) consists of high energy protons, alpha particles, and heavy ions. However, the GCR in LEO is much different than in free space, especially at 0 degree inclination. At this low inclination, only the most energetic particles make it through the geomagnetic field. These high energy particles initiate nuclear interactions in the shielding that produce secondary particles, leading to an increase in exposure. You can see that the dose increases until around 1.5 tonnes/m^2, and gradually declines thereafter. This behavior is analogous to the so-called Pfotzer maximum observed in the Earth's atmosphere [Slaba 2014].

In table 4 we also see that the radiation levels are not monotonically decreasing with increased shielding due to secondary particles created by collisions between GCR and shielding material. For example at 500 km there is a steady rise in the mGy/yr column from 0.01 to 1.25 tonnes/m^2. A rise is also seen in the mSv/yr column above 0.25 ton/m^2 up to 2 tonnes. This indicates that secondary radiation produced by the hull and interior materials will increase the radiation levels experienced compared to less shielding, but not enough to exceed the our limits.

Orbital Inclination and Radiation Levels

All of the radiation data examined so far are from over the equator. This is important because radiation levels for inclined orbits can be a much higher. To understand the effect of orbit inclination note that there is a region of high radiation just below the equator called the South Atlantic Anomaly [Schimmerling 2014] shown in Figure 3. This means that substantially inclined orbits receive much more radiation than equatorial orbits. LEO satellites in inclined orbits pass through the Anomaly perhaps seven times in 24 hours, spending around 20 minutes each time [NCRP 2000 page 68]. Spacewalks are avoided when passing through the anomaly due to the high radiation levels experienced there [Robbins 1996 page 24].

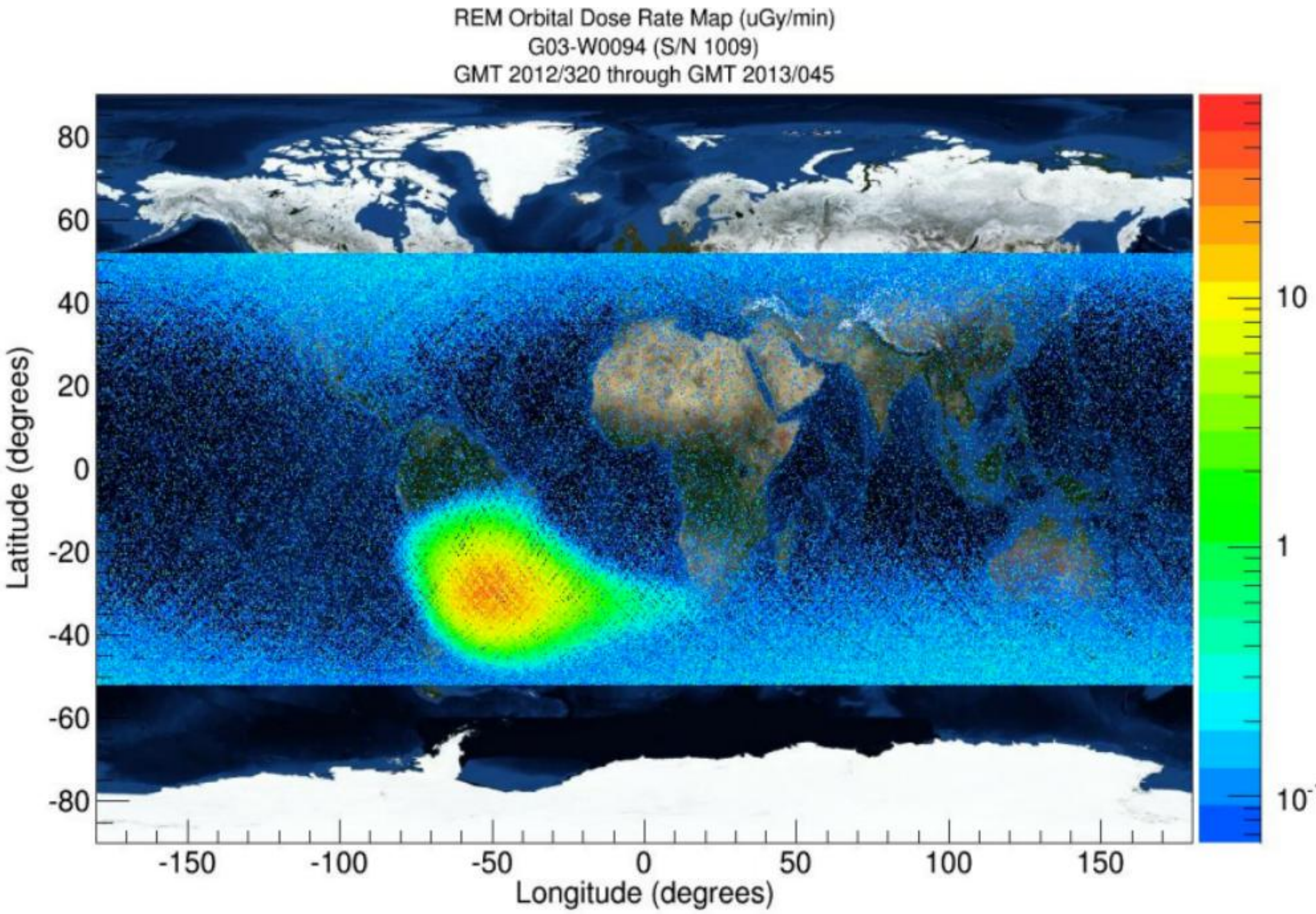


Figure 3 (repeat of Figure 1 for convenience): Radiation measurements taken on the ISS (International Space Station). Each color coded dot is a measurement with blue indicating low levels. Note the high levels of radiation in the South Atlantic Anomaly and very low levels near the equator. These low levels are well below our 6.6 mGy/yr limit, but the ISS orbit is around 400 km, somewhat below the altitude of the computational data presented in the paper. Image credit NASA.

The quantitative effect of inclination can be seen in Table 5, and it is dramatic: space settlements in inclined orbits require multiple tonnes of water shielding to meet the 20 mSv/yr limit even at fairly small inclinations (e.g., 15 degrees). Clearly, from a radiation perspective, LEO settlements should be in equatorial orbits if at all possible.

Mass (tonnes/m^2)	0° (mSv/yr)	15° (mSv/yr)	30° (mSv/yr)	45° (mSv/yr)	60° (mSv/yr)	75° (mSv/yr)	90° (mSv/yr)
0.25	14.6	262.8	636.0	424.1	345.0	335.5	334.0
0.5	12.1	112.1	253.5	178.2	164.0	168.7	170.3
1	13.2	43.4	88.7	79.1	90.3	100.2	102.7
2	14.0	21.6	36.7	45.5	58.9	66.4	68.3
3	12.6	16.4	25.1	33.2	42.4	47.1	48.3
4	10.3	12.3	17.6	23.5	29.4	32.2	32.9
5	7.9	8.9	12.1	16.1	19.6	21.3	21.7
6	5.7	6.3	8.2	10.7	12.7	13.7	13.9

Table 5. This shows the effect of inclination and shielding on radiation levels. The rows indicate the amount of radiation inside a settlement with the given amount of water shielding (not polyethylene). Thus, the levels are not directly comparable to other tables in this paper, but the differences are small. The columns correspond to different orbital inclinations at 600 km altitude. Red indicates that the level meets our 20 mSv/yr limit for adults. All calculations by OLTARIS.

It should be noted that the South Atlantic Anomaly, or at least the peak proton flux, has been drifting westward and northward as the Earth's magnetic field evolves [Fry 2000]. The stability of the South Atlantic Anomaly over long periods of time is unknown.

How Wide is the Low Radiation Window?

Table 6 explores low inclinations to determine how close to equatorial an orbit must be to garner the benefits of avoiding the South Atlantic Anomaly.

500 km	No shielding				
	biological (Dose Equivalent)		physical (Dose)		
inclination	All	GCR	all radiation	GCR	Trapped Proton and Neutron Albedo
deg	mSv/yr	mSv/yr	mGy/yr	mGy/yr	mGy/yr
0	17.68	16.78	10.23	3.194	7.036
1	17.68	16.78	10.23	3.194	7.036
2	17.75	16.81	21.97	3.201	18.77
3	17.89	16.84	51.31	3.208	48.1
4	18.25	16.87	97.74	3.215	94.52
5	18.97	16.91	161.7	3.221	158.5
6	20.56	16.98	274.2	3.247	271
7	22.95	17.06	427.1	3.274	423.8
8	26.96	17.14	656.9	3.292	653.6
9	31.89	17.27	897.1	3.311	893.8
10	40.49	17.39	1217	3.330	1214
11	42.69	17.49	1616	3.358	1613
12	70.7	17.66	2012	3.388	2009
13	94.39	17.85	2567	3.422	2563
14	118.3	18.04	2915	3.462	2912
15	148	18.27	3270	3.505	3266

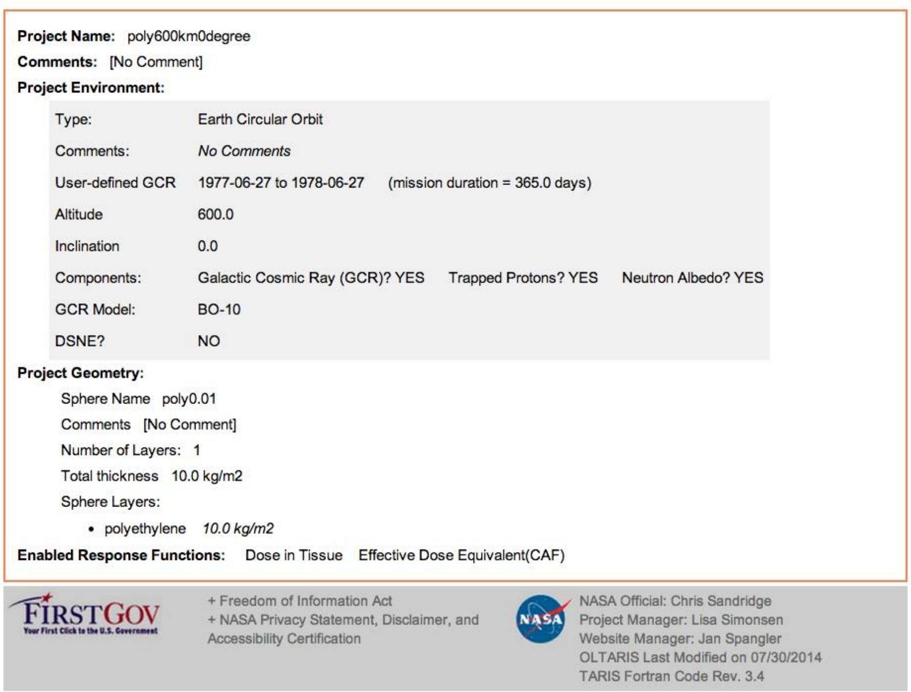
Table 6 shows the nature of radiation near 0 degrees inclination with no shielding. Red indicates that it matches the 20 mSv/yr adult limit or the 6.6 mGy/yr pregnancy limit. Except for column 2 and 4 the limits don't apply as these columns don't represent all of the radiation. These data are for a circular orbit at 500 km. Note that the data are identical for 0 and 1 degree. This is because OLTARIS has a divide by 0 when inclination is 0 so it is changed to 1 degree internally [Sandridge 2015]. The first column is the orbit's inclination. The second is the biological impact. The third is the proportion of the second due to GCR. The fourth is the absorbed radiation, not modified for biological effectiveness. The fifth is the GCR part of the fourth and the sixth is the trapped protons and neutron albedo part for the fourth. All calculations by OLTARIS

Notice that the window of low radiation around 0 inclination is about 10 degrees wide (five degrees north and five degrees south) when considering the radiation limit for the general population only. This is enough so that launch facilities to support settlements in ELEO can be quite some distance from the equator without much delta-v penalty for inclination change. The Guiana Space Center where Ariane launches, for example, is within the window. The take home message is that low-radiation settlements can be a bit off of zero inclination, but not by much.

Note that the pregnancy limit is badly violated in this table but this is for essentially no shielding. However, the pregnancy limit is met for GCR and the trapped protons are easily blocked.

Method

All of the calculations in this paper were made with OLTARIS, a freely available web front end for NASA's sophisticated radiation codes. Figure 4 indicates the parameters used for the LEO calculations (except Table 5). Only the material (the "sphere") and the altitude or inclination were changed for each run. For this study, the model calculates the dose (mGy/yr) for a point in the middle of a sphere of uniform materials and also calculates the biological effect on the body (mSv/yr -- effective dose equivalent) on a model of the female body. Since the body self shields, this results in lower reported levels than if calculated at a point.



Project Name: poly600km0degree
Comments: [No Comment]
Project Environment:

Type:	Earth Circular Orbit
Comments:	*No Comments*
User-defined GCR	1977-06-27 to 1978-06-27 (mission duration = 365.0 days)
Altitude	600.0
Inclination	0.0
Components:	Galactic Cosmic Ray (GCR)? YES Trapped Protons? YES Neutron Albedo? YES
GCR Model:	BO-10
DSNE?	NO

Project Geometry:
Sphere Name poly0.01
Comments [No Comment]
Number of Layers: 1
Total thickness 10.0 kg/m2
Sphere Layers:
- polyethylene *10.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

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NASA Official: Chris Sandridge
Project Manager: Lisa Simonsen
Website Manager: Jan Spangler
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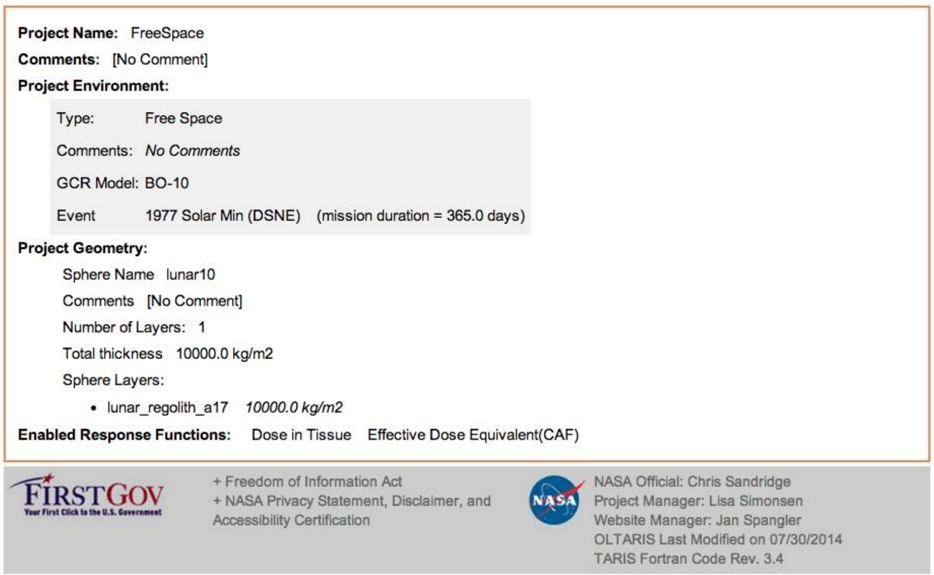
TARIS Fortran Code Rev. 3.4

Figure 4 shows the parameters used for the LEO calculations. Only the materials ("sphere name" which includes the thickness) and the altitude were changed between runs.

Figure 5 indicates the parameters used for the free space calculations. Only the material (the “sphere”) was changed between runs. Calculation results were usually read off the OLTARIS output and entered by hand into a spreadsheet, but for Table 5 the “Copy Data” OLTARIS button was used. The response function measured the dose in tissue using the “Computerized Anatomical Female (CAF)” model. The details of what these parameters mean can be found in the help and reference sections of the OLTARIS web site.



Project Name: FreeSpace
Comments: [No Comment]
Project Environment:

Type: Free Space
Comments: *No Comments*
GCR Model: BO-10
Event 1977 Solar Min (DSNE) (mission duration = 365.0 days)

Project Geometry:

Sphere Name lunar10
Comments [No Comment]
Number of Layers: 1
Total thickness 10000.0 kg/m2
Sphere Layers:

- lunar_regolith_a17 *10000.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

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Figure 5 shows the parameters used for the free space calculations. Only the materials (“sphere name” which includes the thickness) were changed between runs.

Note: We report OLTARIS results for 0 degrees inclination orbit which is what we requested for the computation runs, but internally OLTARIS converts 0 degrees to 1 degree to avoid a divide by zero in the code [Chris Sandridge 2015]. This means that the results presented here are slightly pessimistic, i.e. radiation levels at 0 degrees inclination should be a little lower than those reported here.

Validating the Radiation Model and Thresholds

This study is based on the output of sophisticated radiation models developed by NASA and others. However, models are never completely accurate and the region of space we are interested in does not appear to have received extensive examination.

The OLTARIS LEO radiation model is known to be somewhat inaccurate, and low, for trapped protons and electrons. However, these particles will likely be absorbed by the hull material needed to maintain atmospheric pressure, impact protection, and 1g centripetal force for artificial gravity. The particles of primary interest, relativistic heavy ions (GCR), are probably better modelled as the dynamics are much simpler. The ISS data in Figure 3 are reasonably consistent with the computational results.

Nonetheless, since so much depends on the exact radiation, one or more small satellites with suitable sensors should be sent to, for example, a 450 km by 650 km elliptical orbit with zero inclination. Such satellites must have sensors to measure the flux of high energy, higher mass particles (GCR) which are the primary threat. If other radiation can be measured as well (particularly high energy inner belt protons), so much the better.

Conversions of radiation levels to biological effect are much more error prone than the radiation levels themselves. Indeed, for the fetus and embryo it cannot be done at all with current knowledge [ICRP 2003]. Thus, a focused research effort to understand the biological effects of radiation in ELEO is in order, particularly for children, testes and pregnant women. Preparatory work can be done on the ground, but it is impractical to reproduce the relevant radiation environment on Earth. Thus, spaceflight experiments are necessary. This should involve a small animal centrifuge in orbit to control for the effects of weightlessness. Indeed, multigeneration rodent studies are very difficult without a centrifuge; in weightlessness young mice have great difficulty nursing and often simply starve to death [Burgess 2007].

The importance of understanding space-relevant GCR doses is hard to overstate. These particles are the primary threat and their biological effect is poorly understood. Most animal studies assume that much higher doses for much shorter periods of time are equivalent to year or multi-year exposures, but that is not necessarily the case. Furthermore, settlers will be exposed not for years but for decades. Understanding these particles should be a primary focus of a vigorous research program.

The same studies that examine biological effect can be used to help validate (or modify) the limits chosen (20 mSv/yr for the general population and 6.6 mGy/yr for pregnant women). While the adult general population level is fairly well supported, for children and pregnant women the level will require a great deal of research and may need modification. Thus, studies will need to include multi-generational work to look for problems during pregnancy.

The easiest way to conduct such studies is on the International Space Station (ISS), which is available today and can study rodents (among other animals). However, there is no small mammal centrifuge and the ISS radiation environment is much more extreme than in ELEO since the ISS is in a 51.6 degree inclination orbit. If ISS studies suggest that the problems may be unacceptable, then a suitable biological research station in ELEO will be necessary since the effects should be less given the much lower radiation levels found there.

Settlement Mass

The result that little or no radiation shielding material may be necessary for settlement in ELEO was surprising to the authors. It has far reaching consequences because above the Earth's magnetic field radiation shielding would constitute the vast majority of orbital space settlement mass (see Table 7) and total mass is a good proxy for development difficulty. Table 7 is taken from early space settlement studies [Johnson 1975] and the exact values are not particularly accurate. For example, the mass of interior furnishings is not included and about 5 tonnes/m^2 of lunar regolith radiation shielding was assumed, which is not enough in deep space. However, the mass reductions for ELEO settlements are so enormous that even with inaccuracies it is clear that placing settlements in ELEO requires far, far less materials than in free space.

name	structural mass (tonnes)	air mass (tonnes)	shielding mass (tonnes)	total/non-shielding
multiple dumbbells	75,000	37,000	9,900,000	89
multiple torus	100,000	10,400	9,700,000	89
banded torus	112,000	13,200	7,000,000	57
single torus	4,600	1,900	1,000,000	155
cylinder	775,000	299,000	19,400,000	19
sphere	64,600	35,200	3,300,000	34
dumbbell	400	200	1,400,000	2,334

Table 7: Mass estimates [Johnson 1975] as a function of settlement shape. The vertical dimension lists various possible shapes. The second through fourth columns gives the mass of the structure, air, and shielding respectively. The last column provides the mass reduction factor achieved by eliminating shielding. For example, the total mass can be reduced by a factor of 19 by eliminating the shielding for the cylinder[11].

With our radiation limits the assumption that space settlements need massive shielding requirements falls apart in ELEO. The reason the 1970s studies placed settlements at L5 was proximity to lunar materials which are energetically easier to launch than from Earth. However, eliminating the mass for radiation shielding and moving to ELEO makes launching everything from Earth arguably as easy or easier than delivering a settlement's worth of lunar materials to L5. Indeed, the energy advantage of Earth launch to LEO is about a factor of 19 greater than a Moon launch to ELEO[12]. This is about the same as the radiation shielding mass factor disadvantage for the cylinder in Table 7! This means that the total energy to launch an unshielded settlement from Earth to LEO is (very roughly) the same as the energy to launch the materials for a shielded settlement from the Moon to L5.

Moreover, if materials are launched from Earth, one can send exactly what is needed rather than gathering and processing bulk materials from the Moon, reducing the mass of materials launched even more. Compared to the 1970s studies, this also eliminates the entire extraterrestrial mining, processing and manufacturing infrastructure development assumed to be necessary to build the first orbital settlements. Taking extraterrestrial mining off the critical path for the first settlement allows a much more incremental approach to settling the solar system.

[11] The reason the cylinder value is so low is that the cylinder is very large, with a population of 100,000. The other shapes have populations of 2,000-10,000.

[12] When measured by the square of delta-v and only a little higher when measured using the rocket equation assuming high ISP.

One of the weaknesses in the business plans of asteroidal and lunar mining companies is the size of the market. Since delivering materials to the surface of the Earth is difficult and involves direct competition with Earth resources on home turf, the ideal market is in space. Today that market consists of somewhat over 1,000 robotic spacecraft, only one of which was designed for repair or refueling, and six people on the ISS. However, once ELEO settlements are in place there will be hundreds, and eventually many thousands or more customers in orbit[13]. If realized, this presents a market opportunity that could drive the space mining industry. Of course once ELEO is full, lunar and/or asteroidal shielding materials will be critical to provide adequate shielding for new settlements beyond the Van Allen Belts, creating a very large market indeed.

With no extra shielding beyond the structure, furnishings and atmosphere, a settlement in ELEO is vulnerable to particularly large solar flares if a severe geomagnetic storm is coincident [NCRP 2000 page 42]. Fortunately, at the highest flux levels these are relatively short, usually hours, and dangerous ones are rare [Cucinotta 2012] [ICRP 2012]. In a settlement such as Kalpana One[14] [Globus 2007], a low-g cylindrical swimming pool around the axis of rotation can be used as a solar storm shelter, although we have not yet quantified the amount of shielding occasional SPEs require. In any case, when a solar storm threatens, everyone has to go swimming for a few hours or so, with short breaks when the Earth is between the settlement and the Sun. The children, at least, should find this mandatory swim party quite acceptable!

Settlements in LEO will be subject to atmospheric drag and without reboost will eventually enter the atmosphere and impact the ground. Fortunately, using electric propulsion for reboost requires little mass due to the high propellant velocities (10s of km/sec). For example, at 20 km/sec propellant velocity the Kalpana One space settlement requires around 2.3 tonnes/yr of reaction mass at 600 km, 8.5 tonnes/yr at 550 km, and 18.7 tonnes/yr at 500 km[15]. This activity does require a great deal of energy.

Heavy objects in the 500 km equatorial orbits take centuries to deorbit if abandoned, leaving ample time to deal with any such event. For example, using the Orbital Lifetime Calculator[16] and assuming a settlement with no radiation shielding and a mass per drag area of 950 kg/m^2, deorbit time is about 195 years for an altitude of 500 km.

[13] If settlements are spaced 1,000 km apart at 500 km there is room for about 40 settlements. If a few nearby orbits are settled it is reasonable to expect up to a few hundred settlements in ELEO. If these eventually grow to 10,000 residents or so apiece, the market will consist of a million people or more.
[14] Kalpana one is a 325m long, 250 m radius cylindrical settlement design for a population of perhaps 3,000.
[15] Using the methodology and data at http://spacience.blogspot.com/2012/03/how-to-calculate-drag-in-leo-using.html
[16] http://www.lizard-tail.com/isana/lab/orbital_decay/ accessed on 15 August 2014.

Conclusion

The conclusions of this paper should be considered preliminary and subject to revision as more is learned about the human body's response to radiation, particularly low levels of GCR. This is particularly true with regard to pregnant women, testes and children. Studies to resolve these issues are best conducted in equatorial LEO (ELEO), but the ISS may be a "good enough" platform if a rodent centrifuge is added. There is also uncertainty in all models, including those used here, so a radiation measurement mission to ELEO might be in order. However, we believe our findings have a good chance of holding up under further examination.

First, it appears that 20 mSv/yr and 6.6 mGr/yr are reasonable limits for a space settlement's general population and pregnant women respectively. This is higher than the average background radiation experienced by most people on Earth, but there are many inhabited parts of the world where background radiation approaches or even exceeds this level.

Second, given these limits, space settlements in ELEO orbits may not require any dedicated radiation shielding at all, or only small amounts. This has strong implications for the location of the first orbital space settlement which, contrary to previous belief, may be easier to build in ELEO using only launch from Earth rather than depending on extraterrestrial mining, processing and manufacture for bulk materials. This is because of the shielding provided by Earth's magnetic field and by the Earth itself. Of course, a settlement in ELEO is better positioned for commerce with Earth than settlements in higher orbits or on the Moon or Mars.

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