Orbital Space Settlement Radiation Shielding

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Abstract

We examine the radiation shielding requirements for protecting the inhabitants of orbital space settlements. Based on the literature, we recommend a limit of 20 mSv/year for the general population and 6.6 mGy/year for pregnant women based on the most relevant existing standards, existing data and background radiation on Earth. Extensive 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 effects of the low-level continuous high-energy particle radiation characteristic of ELEO on human tissue that need to be resolved. Thus, our conclusions should be considered preliminary.

Introduction

Radiation levels in space are significantly higher than on Earth and this can have a number of negative effects on the human body including but not limited to birth defects, cancer (particularly leukemia), cardiovascular problems, central nervous system problems, cataracts and premature sterility [Fry 1989][Fry 1996][Fry 2000][Wrixon 2008][Straume 2010]. However, radiation levels can be reduced either by shielding materials or by electromagnetic forces.

In this paper we examine the radiation protection requirements for permanent human settlements in orbit. Careful examination of figure 1 indicates that space settlements in Low Earth Orbit (LEO) that stay directly above the equator will receive very little radiation compared to higher inclination orbits. Radiation in deep space, beyond Earth's magnetic field, is much greater than in LEO, even in high inclination orbits. This is because of the protective effect of the Earth's magnetic field. These observations lead us to a radically easier approach to establishing the first space settlements.

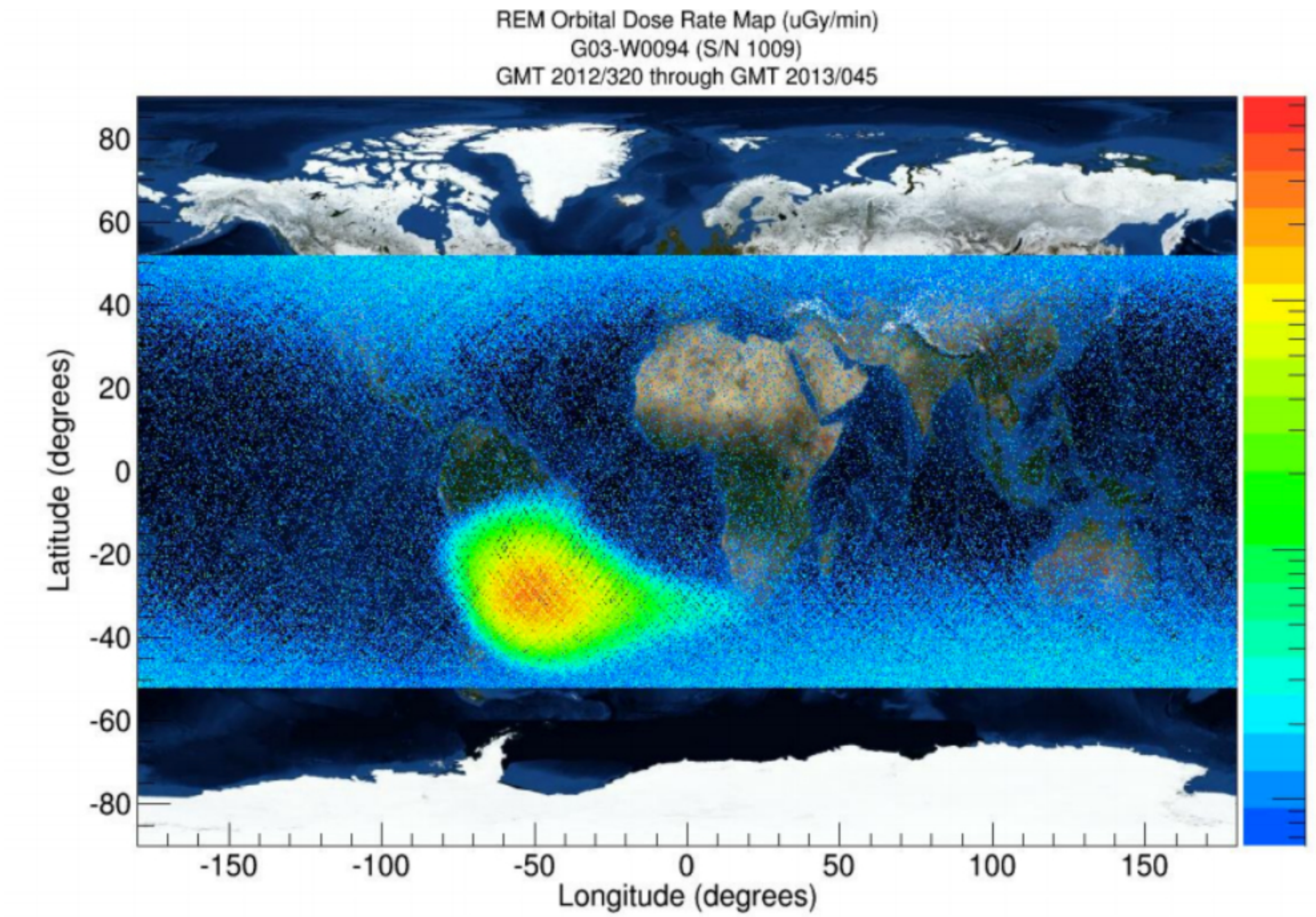

Figure 1: Radiation measurements taken on the ISS (International Space Station) at about 400 km altitude. Note that most of the radiation is found above South America and the South Atlantic. Zero inclination orbits do not pass through this region and spacecraft in these orbits receive relatively little 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.

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 cities, roughly 4.5 tons per square meter of hull, would be sufficient to meet a 5 mSv[2]/year limit

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

[2] The modern measure of absorbed radiation is the Gray. The biological impact of a given level of radiation is measured in Sieverts. Conversion of Grays to Sieverts depends on the type of radiation

for settlers at the Earth-Moon L5 point. This shielding mass is far more than the structural mass, atmosphere, and interior accommodations combined. This drove the choice of L5 as the settlement location so that lunar materials could be used for radiation shielding. An elaborate mining and transportation system was designed to deliver large quantities of lunar regolith to L5.

Unfortunately, the 4.5 tons 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 adults and 6.6 mGy/year for pregnant women requires 10-11 tons of lunar regolith per square meter, more than double the amount suggested by these early studies.

Fortunately, radiation shielding mass requirements can be substantially reduced by using better materials and/or by placing settlements in Low Earth Orbit (LEO) rather than above the Van Allen belts. Specifically, to meet the 20 mSv/year and 6.6 mGy/year limits our calculations suggest that 6-7 tons 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 or lower equatorial Earth orbit require little or no dedicated shielding at all, reducing settlement mass by a factor of 20 or more. If no dedicated radiation shielding is necessary, besides being far less massive and much closer, the first settlements may not need 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.

There is one study that examines radiation shielding requirements for Mars settlement [Straume 2010]. However, unlike orbit, Mars has ample materials for radiation shielding on the surface so the focus is on transit of settlers to Mars, which is on the order of a half year.

Radiation in Space

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

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involved but on 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 mSv to mGy, the mGy figure is always larger than the mSv for the same point.

The first class is caused by solar storms, also known as Solar Proton Events or SPE. These happen perhaps 5 to 10 times per year, except near a solar minimum [Cucinotta 2012]. The particles from these storms are directional, going outward from the Sun along magnetic field lines [Robbins 1996] in a relatively small area, typically last for several hours at peak exposure rates, and are dominated by protons with an energy of one MeV up to a few hundred MeV. Severe storms may require extra shielding for periods of a few hours to days or perhaps even weeks [Fry 2000 page 38]. Fortunately, dangerous solar storms that impact Earth and its environs are rare and the Earth's magnetic field is usually protective.

The second class of dangerous radiation consists of galactic cosmic rays (GCR). GCR are made up primarily of nuclei with no electrons, can travel at relativistic speeds, and are omni-directional. Around 98% of GCR are protons and heavier with the rest being electrons and positrons. Of the larger particles, 87% are protons and 12% Helium. Most of the dose is from these plus carbon, neon, oxygen, silicon and iron [Fry 2000 page 4]. Energy varies from less than one MeV/u[3] 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 of the 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 [Fry 1989 page 57]. Fortunately, GCR is at a fairly low level.

There is a third class of space radiation which is relevant to settlements in Low Earth Orbit (LEO). This consists of trapped electrons and protons in the Van Allen belts [Schimmerling 2014] which can result in somewhat high radiation levels in relatively low Earth orbit (very roughly 1,000 - 60,000 km). However, these are light 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.

Radiation in Low Earth Orbit (LEO)

Most of the known negative effects of radiation require 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 [Fry 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 LEO from most of the effects of solar storms. For example, during a large flare in October of 1989 shuttle crews

[3] MeV/u stands for million electron volts per neutron or proton.

did not measure an increase in radiation, although there was a 30-40 mGy increase in the Mir space station, which was at a higher inclination. In general solar storm effects are only measurable in spacecraft when at high latitudes [Robbins 19960 page 17]. In LEO even a large storm poses relatively little risk unless the storm 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 [Fry 2000 page 42].

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

In LEO trapped particles are of concern in higher orbits and are inner belt protons, electrons are found at higher altitude [Robbins 1996 page 12]. Most protons in LEO exhibit energies of 6-500 MeV and neutrons 10 KeV to 2 MeV [Fry 2000 page 70]. These particles are relatively easy to shield against.

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 [Fry 1989 page 69] with lethality at 2,000-4,000 mGy [Fry 1989 page 70].

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

Long term stochastic effects, especially cancer and particularly leukemia, are the primary target of radiation standards for astronaut radiation exposure. While radiation exposure is associated with leukemia, not all studies have found an increase [Fry 1989 page 109]. Exposure to radiation reduces lifespan and cancer is responsible for this effect [Fry 1989 page 85]. Traditionally, the space program has sought to limit increased fatal cancer risk to 3% 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].

Radiation can also cause sterility in both men and women, although men are more susceptible [Fry 2000 page 104]. An acute dose of 150 mGy can cause a sperm count decrease in about 40% within a few months and 300 mGy can cause temporary sterility [Fry 1989 page 78].

Unfortunately, much of what we know about radiation effects on the human body come 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. Furthermore, there is a controversy over the size and nature of the biological effects of the low dose-rate radiation characteristic of GCR [Fry 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 [Fry 2000 page 115].

There have also been a number of studies of people exposed to radiation at work, e.g., nuclear power plant operators. These indicate a possible small effect on fertility in both men and women [Straube 1995, Doyle 2001]. The testis are more vulnerable to radiation effects than ovaries [Fry 2000 page 138][Fry 1996 page 42] and there is evidence that unlike most tissue, spreading the dose out in time, characteristic of occupational and space settlement exposure, may increase damage to the testis. In a survey paper, Brent found that to negatively affect pregnancy and fetal DNA, a fairly high radiation level is required [Brent 2012], well above our proposed 20 mSv/year and 6.6 mGy/year limits. However, these studies do not involve the high energy massive particles that characterize the most dangerous parts of GCR.

Radiation studies on animals are usually limited to short time periods because that is easier to do. Short periods of higher flux are used to simulate lower levels for longer periods. So, due to the nature of the data, relatively little is known about the biological effect of long periods of low-level high-energy high-mass particles such as relativistic iron nuclei. After all, one could not predict the effects of sunlight on human skin if subjects were illuminated with a year's worth of solar optical and UV radiation in five minutes. Thus, the conversion of low GCR radiation levels to biological effectiveness must be viewed with some suspicion until improved data are available.

The problem is further confused by secondary particles. When an iron nucleus (or other heavy particle) passes through a material and strikes another nucleus, a shower of secondary particles is created. 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.

We now attempt to determine acceptable radiation standards for space settlement residents, particularly pregnant women. We then quantify this 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.

We have chosen 20 mSv/year for the general population, with caveats, to match the most relevant existing practice (see next paragraph), and 6.6 mGy/year for pregnant women to avoid known problems by a wide margin. This is well above the 5 mSv/year used in the 1970s studies, which is, in our opinion, unnecessarily conservative. Our limits are well below the limit for deterministic radiation effects[4], 500-2,000 mGy (depending on the tissue) [Clement 2012] and are intended to limit stochastic effects such as cancer. Excess deaths from cancer have only been demonstrated for doses around 200 mGy [Fry 2000 page 109], which would require 30 years of exposure at 6.6 mGy/yr.

We first examine the 20 mSv/year limit for the general population followed by a discussion of the 6.6 mGy/year limit for pregnant women.

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

Relevant information to consider include:

- The International Commission on Radiological Protection (ICRP) recommends a 20 mSv/yr limit for occupational radiation exposure [Wrixon 2008].
- The Japanese government uses 20 mSv/yr to determine which residences may be re-occupied after evacuations due to the Fukushima nuclear power plant accident [McKirdy 2014].
- The National Commission on Radiological Protection (NCRP) recommendations no more than 50 mSv/year for radiation workers in the U.S. [Space Radiation Analysis Group 2014][Fry 1989 page 161] and 2,500 mSv lifetime [Fry 1989 page 161].
- The NCRP recommends an lifetime occupational limits for space workers of age times 10 mSv [Fry 1989 page 156], which is a great deal less than the NCRP recommendation

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

for terrestrial radiation workers presumably because only adults (professional astronauts) are the subject to this recommendation..

- The NCRP recommends 10 year limits for professional astronauts that varies from 40-300 mSv/yr depending on age and gender [Fry 2000 page 143 table 6.2].
- The annual limit for US astronauts is 500 mSv/year 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].

20 mSv/year is considerably above the average background radiation in the U.S., 3.1 mSv/year (not including medical X-rays, etc.) [Linnea 2010, NRC 2010]. However, this is an average, and much higher levels exist locally. There are several large regions of Europe, particularly in Spain and Finland, with levels over 10 mSv [World Nuclear Association 2014] and there are inhabited parts of the world with much higher levels with no known major negative effects.

For example, the highest recorded background radiation on Earth is in Ramsar, Iran, where monitored individuals have received an annual dose up to 132 mGy/year, far above our 20 mSv/year limit [Ghiassi-nej 2002]. Other high natural radiation areas include Yangjiang, China, Kerala, India, and Guarapari, Brazil. The background radiation in parts of Karala, India is 30 mSv/year [Brooks 2010 page 31].

Radiation limits for American astronauts are chosen to increase lifetime fatal cancer risk by no more than three percent, which was below the accidental death rate for many professions [Slovic 1996a page 3] when the limit was created. 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 (and other) treatment before any settlers are exposed to space radiation. Indeed, for some radiation effects, such as cataracts, there are effective treatments today. Moreover, in the small, self-contained environment of a space settlement it may be possible to limit chemical carcinogens to the point that total cancer risk is decreased relative to Earth.

Thus, it seems that 20 mSv/year is a reasonable and conservative level 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.

Radiation Limit for Pregnancy (6.6 mGy/year)

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/year) primarily based on data and recommendations found in ICRP 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 [Valentin 2000] and [Valentin 2003] for various radiation threats to the fetus and embryo and published these 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) [Valentin 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 [Valentin 2003].

As the effects of radiation during pregnancy is a complex subject. We have abstracted the most relevant sections of the ICRP pregnancy-related publications [Valentin 2000] and [Valentin 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 [Valentin 2003].
- [Wrixon 2008] recommends a 1 mSv/pregnancy limit for women with occupational radiation exposure and [Valentin 2000] recommends 1 mGy/pregnancy. This is in addition to the background radiation, which, as noted above, is much higher than than 5.6 mGy/year (which would bring the total to our 6.6 mGy/year limit) in many places on Earth.
- [Valentin 2003] notes one study suggesting that 10 mGy of medical radiation[5] 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.
- [Valentin 2003 Table 4] indicates that fetal absorbed dose below 5 mGy per pregnancy (our suggested limit) shows no increase in childhood cancer or increase in

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

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 [Valentin 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. [Valentin 2003 paragraph 376].
- 100 mGy or less can cause pre-implantation death during some radiosensitive stages, but this is far above what would be experienced if radiation is limited to 5 mGy/pregnancy and preimplantation lasts only a few days [Valentien 2003 paragraph 409].
- In a very large study[6] 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 [Valentin 2003 paragraph 397]. If there is no threshold, and the effect is linear to zero, that would imply 0.35-3.2 cancer deaths per 10,000 people 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 [Valentin 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 [Valentin 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 [Valentin 2003 paragraph 424], which is the case for space settlers.

For comparison with Earth-bound pregnancies and cancer:

- When pregnant women are exposed to only Earth background radiation there is a 15% spontaneous abortion rate, 2-4 percent chance of major malformations, a 4% chance of retardation and 8-10% chance of genetic disease [Valentin 2003]. Not all of this is necessarily due to radiation.
- Lifetime cancer risk today is about 1 in 3 and cancer caused death about 1 in 5 [Valentin 2003].

All this suggests 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/year. This is 20 x less than the threshold for considering pregnancy

[6] 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.

termination and is the highest level with no reported increase in childhood cancer in [Valentin 2003 Table 4]. Note that if this level is exceeded by a small amount, additional shielding could be temporarily added to the homes of pregnant women to meet the limit.

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

Female Fertility

Note that at levels below our limits there is little chance of long term female infertility, which seems to require at least 1,000 Gy (150 years equivalent at doses below 6.6 mGy/yr) or more [Fry 1989 page 77], and male and female mice irradiation with Co60 gamma rays at over 7,000 mGy/year for ten generations resulted in normal reproduction [Fry 2000 page 104]. Table 5.6 in [Fry 2000] suggests that below 600 mGry (90 years equivalent) of 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 equivalent).

Testes

The testes are very sensitive to radiation [Fry 2000 page 104][Fry 1989 page 78]. Our limit for adults and pregnant women are well below other proposed limits:

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

[Herrman 1997] found that the mean tolerance for decreased sperm counts may require between 2,000-3,000 mGy (300-450 years equivalent). All of this suggests that our 20 mSv/yr 6.6 Gy/yr limits may be adequate.

There is one study of Romanian workers that suggest caution and additional research [Popescu 1975]. This study looked at 72 men with occupational exposure who received an estimated 4.8 to 93 mGy/yr. As a group, they suffered higher rates of hypospermia, asthenospermia and teratospermia than controls (42 men with similar occupations having no radiation exposure). The experimental group's wives also experience a greater than normal number of miscarriages and stillbirths. However, although many men in the experimental group experienced more problems than the controls, the paper does not include information about the distribution of issues within the experimental group and there is no way to tell if the men exposed to relatively low levels had normal function or not. Furthermore, the estimates of exposure may not be particularly accurate. Thus, while cautionary and suggesting more research is necessary, this data does not call for limits lower than 20 mSv/yr and 6.6 mGy/yr at the moment.

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 [Clement 2015 paragraph 132] might suggest otherwise. However, although cancer risk for a given radiation load is usually somewhat greater for children than adults the difference is not always great or in that direction. [UNSCEAR 2013 paragraph 47 f] 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 GCR, the primary threat for space settlement, but rather short periods of intense radiation from medical or nuclear bomb exposure data.

[UNSCEAR 2013 paragraph 47 a] estimates that for a given radiation dose children's lifetime cancer risk might be 2-3 greater than for people of all ages but this is "uncertain." [UNSCEAR paragraph 47 e] 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, 10% cancer risk is lower with the remainder being the same or the data inconclusive [UNSCEAR 2013 paragraph 47 c]. [Clement 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 for a given radiation exposure is often less than for adults [UNSCEAR 2014 paragraph 80], although it is higher for longer periods because children being younger have longer remaining lifetimes. Finally, [Clement 2015 paragraph 47d] notes that "projections of lifetime risk for specific cancer types following exposure at young ages are statistically insufficient."

Note that the Japanese government has allowed residents to return to, or stay in, their homes near the Fukushima nuclear plant when radiation levels are 20 mSv/year or less. For now, we assume that the combination of limits for adults and the fetus will be sufficiently protective for children. This is an area requiring additional research.

Miscellaneous

It should also be noted that there is evidence that low levels of radiation stimulate an adaptive response from the human body that reduces the radiation damage one might otherwise expect [Ghiassi-nej 2002]. There are similar results for rodents in some circumstances [Valentin 2003]. Otherwise damaging doses to the skin (2,000 Gy) are much less effective if the radiation is spread out over six weeks or more [Fry 2000 page 92]. The pattern of radiation exposure for typical LEO missions to date, long term low rates punctuated by higher rates when passing through the South Atlantic Anomaly, results in less damage than a single dose of the same magnitude. However, there is evidence that the opposite in the case for the testes [Fry 2000 page 103].

In addition to meeting our limits, 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.

Radiation Shielding Materials

The best shielding materials for 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, as we have seen, 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). It is a little better than water because carbon nuclei are smaller than oxygen, making for fewer collisions and less mass for the same number of hydrogen atoms. Note that many asteroids are rich in carbon compounds and water.

Lunar regolith, which has little hydrogen, is a poor radiation shielding material. This is illustrated by Table 2 which shows the radiation level expected in “free space” (above the Van Allen belts 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/year than with polyethylene or water.

	polyethylene		water		lunar regolith	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
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. The first column lists tons of shielding per square meter, the other columns list different materials and measures. The mGy columns are a (computational) measure of radiation absorbed by a person inside the shielding, the mSv columns are biological impact of that absorption. The red color indicates that values are less than 20 mSv/year or 6.6 mGy/year. Note also 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, so the 1977 time period is appropriate and conservative. 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. 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. Radiation levels above the Earth's magnetic field are much higher than in LEO.

On the surface of Mars or the Moon approximately 50% of the GCR is blocked by thousands of km of rock[7]. Thus, Table 2 can be used to determine rough radiation shielding requirements for surface settlements. Levels in the table below 40 mSv/yr and 13 mGr/yr meets our limits for surface settlements, which works out to roughly two tons 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 tons of material per square meter of hull. Note that at 600 km one ton of shielding is more than adequate to meet the 20 mSv/year and 6.6 mGy/year limits. The shielding required to meet these limits rises with altitude as the Earth blocks less of the sky and the magnetic field weakens.

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

	600 km		700 km		800 km		900 km		1000 km	
tons/ m^2	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy
1	14.0	5.2	25.3	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/year (biological impact) and mGy/year (radiation absorbed). Rows are levels calculated for polyethylene shielding in tons per square meter of settlement hull. The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets our 20 mSv/year or 6.6 mGy/year limits. All calculations use OLTARIS.

Noting that at 600 km with a single ton of shielding the radiation expected, 14.0 mSv/year, is well under the 20 mSv/year 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	
tons/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	14.0	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 tons 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/year limit or the 6.6 mGy/year 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/year and only a tiny (equivalent to polyethylene 0.01 ton/m^2) amount to meet the 6.6 mGy/year limit. The ISS has an average of about the equivalent of 200 kg/m^2 aluminum shielding [Cucinotta 2013]. 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.

There is a very high radiation level (mGy/year 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.

The radiation levels are not monotonically decreasing with increased shielding due to secondary particles created by collisions between GCR and shielding material. For example, there is a steady rise, at 500 km, of the mGy/yr column from 0.01 to 1.25 tons/m^2. A rise is also seen in the mSv/yr column above 0.25 ton/m^2 up to 2 tons. 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.

Note that there are local minima and maxima in radiation levels at 600 km as well. For example, there is a local minimum at 0.25 tons shielding and a local maximum at 1.75 tons, with radiation increasing between the two in the mSv/yr column. The minimum is caused by the shielding blocking protons and the maximum by unabsorbed GCR secondary radiation which causes more damage than the primary particles.

Figure 2 illustrates the physics behind this effect.

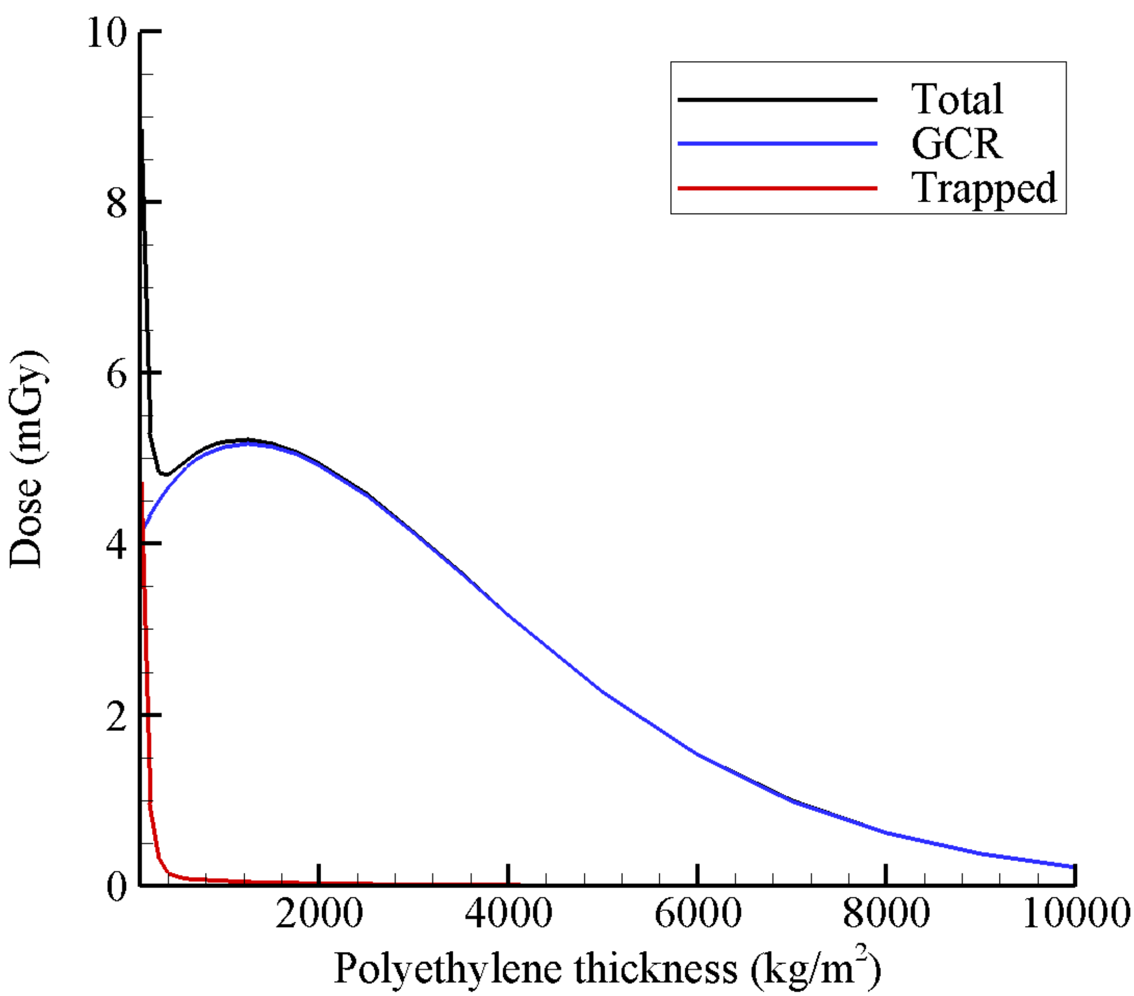

Figure 2: The trajectory was circular at 600 km and 0 degree inclination. The trapped

proton component (red line on plot) consists mainly of lower energy protons that are stopped with little shielding. The dose profile from this part of the environment 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 GCR 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 the dose increases until around 1.5 tons/m^2, and gradually declines thereafter. This behavior is analogous to the so-called Pfotzer maximum observed in the Earth's atmosphere [Slaba 2014].

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 in protons trapped in the Anomaly [Fry 2000 page 68]. Space walks are avoided when passing through the anomaly due to the high radiation levels experienced there [Robbins 1996 page 24]

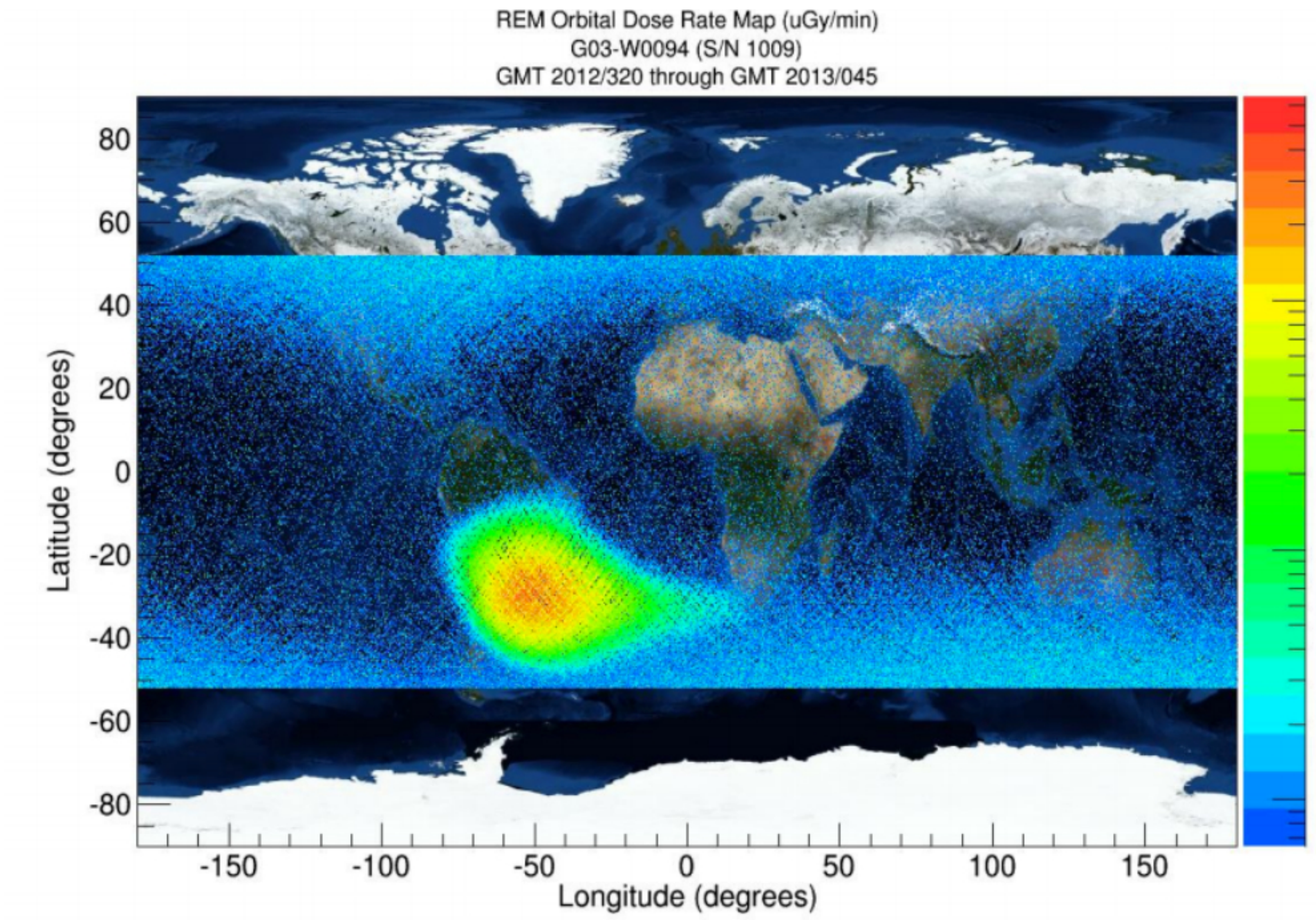

Figure 3 (repeat of figure 1 for convenience): Radiation measurements taken on the ISS (International Space Station). Note the high levels of radiation over the South Atlantic and much of South America and very low levels near the equator. These low levels are well below our 6.6 mGy/yr limit, but the 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 tons of water shielding to meet the 20 mSv/year limit even at fairly small inclinations. Clearly, from a radiation perspective, LEO settlements should be in equatorial orbits if at all possible.

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 5 shows us that at 0 degrees inclination radiation levels are very low and at 15 degrees they are quite high. Table 6 explores the region between these two to determine how close to equatorial an orbit must be to garner the benefits of avoiding the South Atlantic Anomaly.

Mass (tons/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, not polyethylene, shielding. 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/year limit for adults. All calculations by OLTARIS.

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 the biological impact. The third the proportion of the third due to GCR. The fourth is the absorbed radiation, not modified for biological effectiveness. The fifth the GCR part of the fourth and the sixth 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) considering the general population limit 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. Also note that the GCR component of the radiation rises only gradually with inclination, but the trapped proton and neutrino component increases quickly and dramatically. These particles are easy to shield. 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 radiation for a point in the middle of a sphere of uniform materials and also calculates the biological effect on the body when placed at this point.

Figure 5 indicates the parameters used for the free space calculations. Only the material (the "sphere") 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: 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)

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

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)

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

Note: we report OLTARIS results for 0 degrees inclination orbit as 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, 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 levels it may be wise to send a small satellite with suitable sensors to the region, say a 450 km by 650 km elliptical orbit with zero inclination. It must have sensors to measure the flux of high energy, higher mass particles (GCR) as these are the primary threat. If other sources of 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 [Valentin 2003]. Thus, a focused research effort to understand the biological effects of radiation in ELEO is in order, particularly for children, testies 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 as 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. The primary threat is these particles 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 the proposed research program.

The same studies that examine biological effect can be used to help validate (or modify) the limits chosen (20 mSv/year for the general population and 6.6 mGy/year for pregnant women). While the adult general population level is very well supported, for children and pregnant women the level will require a great deal of research and probably 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 as the ISS is in a 51.6 degree inclination orbit (see Table 5). 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 is the vast majority of orbital space settlement mass (see Table 7) and total mass is a good proxy for development difficulty. Table 7 is 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 they assumed around 5 tons/m^2 of radiation shielding, which is not enough in deep space. However, the mass reductions 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 (tons)	air mass (tons)	shielding mass (tons)	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 from [Johnson 1975] as a function of settlement shape. The vertical dimension is various possible shapes. The second through fourth column are the mass of the structure, air, and shielding respectively. The last column is the mass reduction factor achieved by eliminating shielding. For example, eliminating the shielding for the cylinder reduces total mass by a factor of 19[8].

[8] 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.

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 settlements worth of lunar materials to L5. Indeed, the energy advantage of Moon launch over Earth launch to ELEO is about a factor of 19[9], 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 assumed to be necessary to build the first orbital settlements. Taking extraterrestrial mining out of the critical path for the first settlement allows a much more incremental approach to settling the solar system.

One of the weaknesses in the business plans of asteroidal and lunar mining companies is the size of the market. As 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 is designed for repair or refueling and six people in the ISS. However, once ELEO settlements are in place there will be hundreds, and eventually many thousands or even more customers in orbit[10]. 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 may be vulnerable to particularly large solar flares if a severe geomagnetic storm is coincident [Fry 2000 page 42]. Fortunately, at the highest flux levels these are relatively short, usually hours, and dangerous ones are rare [Cucinotta 2012] [Clement 2012]. In a settlement such as Kalpana One[11] [Globus 2007], a low-g cylindrical swimming pool around the axis of rotation can be used as a solar storm shelter. When a solar storm threatens, everyone has to go swimming

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

[10] 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 LEO. If these eventually grow to 10,000 residents or so apiece, the market will consist of a million people or more.

[11] Kalpana one is a 325m long, 250 m radius cylindrical settlement design for a population of perhaps 3,000.

for a few hours, 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 tons/year of reaction mass at 600 km, 8.5 tons/year at 550 km, and 18.7 tons/year at 500 km[12]. 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[13] 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.

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, testies 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/year and 6.6 mGr/year 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.

[12] Using the methodology and data at http://spacience.blogspot.com/2012/03/how-to-calculate-drag-in-leo-using.html

[13] http://www.lizard-tail.com/isana/lab/orbital_decay/ accessed on 15 August 2014.

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