Orbital Space Settlement Radiation Shielding

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Abstract

We examine the radiation shielding requirements for protecting the inhabitants of space settlements located in orbit. In particular, we recommend a threshold of 20 mSv/year based on the most relevant existing standards. Space settlement studies in the 1970s assumed that lunar regolith with a mass equivalent to Earth's atmosphere above high altitude cities, roughly 5 tons per square meter, would be sufficient to meet a 5 mSv/year threshold at the Earth-Moon L5 point, their recommended settlement location. Using OLTARIS, NASA's online radiation computational tool, we found this to be far too little for their 5 mSv/year threshold. Even at our 20 mSv/year threshold about 10 tons/m^2 of lunar regolith is required. Fortunately, radiation shielding mass requirements can be radically reduced by using better materials and/or by placing settlements in low Earth orbit (LEO) rather than above the Van Allen Belts. Specifically, 6-7 tons of water or polyethylene radiation shielding per square meter of hull is sufficient in free space and settlements in a circular 500-600 km equatorial Earth orbit may require no shielding at all to meet the 20 mSv/year threshold. This has strong implications for the best paths towards space settlement as the first settlements may not need extraterrestrial mining and processing. For settlements in LEO, transportation to and from Earth is (relatively) easy, implying a smaller step between large space hotels or low-g retirement homes and the first settlements. It is important to note that there are significant uncertainties in our understanding of the effects of low-level continuous high-energy particle radiation on human tissue that, when resolved, may invalidate these findings.

Introduction

This paper examines the radiation protection requirements for permanent human settlements in orbit. 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 space settlements in orbit suitable for permanent habitation including raising children. One of the system drivers was radiation as the location chosen was the Earth-Moon L5 point which is one lunar distance from Earth and the Moon and is well above the Van Allen Belts. Thus, for these studies, the Earth's magnetic field provided no radiation protection.

Radiation levels in space are significantly higher than on Earth and this can have a number of significant negative effects on the human body including but not limited to birth defects, cancer, cardiovascular problems, central nervous system problems, cataracts and, particularly important, premature sterility [Straume 2010]. This radiation can be blocked either by shielding materials or electromagnetic forces. The 1970s studies chose materials and the mass of the resulting settlement designs is dominated by radiation shielding, 4.5 tons of lunar regolith per square meter of hull. This was intended to duplicate the radiation protection provided by the Earth's atmosphere, which is 10 tons/m^2 at sea level and about 5 tons/m^2 at high altitude cities. This shielding mass is far more than the structural mass, atmosphere, and interior accommodations combined. Thus, acquiring radiation shielding mass was considered one of the most difficult technical challenges in developing orbital space settlements. This drove the choice of L5 as the settlement location so that lunar materials could be used for radiation shielding. An elaborate transportation system was designed to deliver large quantities of lunar regolith to L5. It should be noted that L5 is well above the protective effects of Earth's magnetosphere and the 4.5 tons of lunar regolith is now known to be insufficient as it is not a very good shielding material (see below).

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

There is one study by Straume et al. that examines radiation shield 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. Staume's study examined the limiting threat, i.e., what is the most serious risk that, if one has enough shielding to reduce it to acceptable levels, all other threats will be taken care of. Studies of non-human primates found that oocytes[1] are extremely radiosensitive during gestation. Indeed, 50 mSv[2] may be sufficient, during gestation, to kill an embryo before the woman is aware she is pregnant. At these levels we expect an effective early onset of infertility. In addition, oocytes are not replenished during a woman's lifetime and there are a limited number of these, all present at birth. As a result, in our study, we looked at radiation damage to female ovaries and assumed that if these can be kept healthy then radiation to other organs and tissue will be acceptable.

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[1] The cells that develop into eggs.

[2] The modern measure of radiation is the Gray. The biological effect of a given level of radiation is measured in Sieverts. Conversion of Grays to Sieverts depends not only on the type of radiation involved but on the tissue involved. mSv stands for milli-Sievert, or one thousandth of a Sievert.

Radiation in Space

There are two major major classes of dangerous radiation in space [Schimmerling]:

One class is caused by solar storms. These happen 5 to 10 times per year, except near a solar minimum [Cucinotta 2012]. Furthermore, these storms are directional, going outward from the Sun in a relatively small area, last hours at peak exposure rates and are dominated by protons with an energy of one MeV up to a few hundred MeV. Fortunately, protons have small mass (comparatively) and are relatively easily blocked.

If the second class of dangerous radiation, galactic cosmic rays (GCR), is adequately shielded against then solar storms will cause few problems. GCR are made up primarily of nuclei with no electrons, can travel at relativistic speeds and are omni-directional. 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 magnetic activity allowing more GCR into the inner solar system, but this is limited to energies less than roughly 2,000 MeV/u. [Cucinotta 2012] While most of the nuclei involved are low atomic number, the most dangerous of the GCR particles are iron nuclei. Fortunately, GCR is at a fairly low level.

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, which involved very high radiation levels for short periods of time which doesn't necessarily generalize to long term exposure to low level GCR. 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]. In a survey paper, Brent found that to negatively affect pregnancy and fetal DNA requires fairly high radiation levels, well above the proposed 20 mSv/yr threshold [Brent 2012]. 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 study. 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 iron nuclei. Thus, the conversion of GCR radiation levels, which can be easily measured, to biological effectiveness must be viewed with suspicion and improved data and understanding may affect the results presented here.

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 smaller 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

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

can worsen radiation damage by creating secondaries, so shielding must be thick enough to absorb most of the secondaries as well.

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] which can result in somewhat high radiation levels in relatively low Earth orbit (roughly 1,000 - 60,000 km). However, these are light particles with relatively little energy that can be stopped by minimal shielding.

For the purpose of this paper, we hypothesize that if settlement radiation shielding is sufficient to keep GCR damage of human ovaries to an acceptable level then all other sources of space radiation for all other tissues will be acceptable. We quantify this level with OLTARIS, NASA's web front end to sophisticated radiation modelling software [OLTARIS 2011, OLTARIS 2014].

Radiation Threshold for Space Settlement

The amount of shielding thought necessary to protect settlers from the space radiation environment depends heavily on the threshold chosen. We have chosen 20 mSv/year, with caveats, to match the most relevant data point: the radiation threshold for allowing people to return after the Fukushima nuclear accident [McKirdy 2014]. This is well above the 5 mSv/year used in the 1970s studies, which is, in our opinion, unnecessarily low.

The threshold used by the Japanese government to determine which residences may be re-occupied after evacuations due to the Fukushima nuclear power plant accident is 20 mSv/year. 50 mSv/year is the threshold for radiation workers in the U.S. [Space Radiation Analysis Group 2014]. 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/yr is considerably above the average background radiation in the U.S., 3.1 mSv/year (not including 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/yr threshold [Ghiassi-nej 2002][4]. Other high natural radiation areas include Yangjiang, China, Kerala, India, and Guarapari, Brazil with no apparent major negative effects. Thus, it seems that 20 mSv/yr is a reasonable level to use for the present study, being aware that additional research is needed and this threshold may need to be changed as better data and theory become available.

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[4] For a given level measured in Grays, at least in our study, the value in Sieverts is much larger.

It should also be noted that there is some 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]. This is hard to study and should not be considered definitive by any stretch of the imagination, but may make the low levels of GCR expected by space settlers more acceptable than we currently believe.

Clearly, people moving from Earth to a space settlement can expect to be exposed 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. Large numbers of electrons are pulled out of position as the particle passes through the material, transferring energy from the particle and eventually bringing it to rest. Liquid hydrogen might be the ideal shielding material from this perspective, but 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/or water.

Lunar regolith, which has little hydrogen, is a poor radiation shielding material. This is illustrated by Table 1 which shows the radiation level in “free space” (above the Van Allen Belts) expected 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 to 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	193	85	199	86	274	109
2	136	52	146	54	261	82
3	90	31	100	34	221	62
4	57	18.5	66	21	172	48
5	35	10.8	42	12.5	126	37
6	20.9	6.3	26.3	7.5	89	28
7	12.2	3.6	16	4.4	61	20.9
8					40	15.1
9					26.1	10.5
10					16.6	7.1

Table 1: 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. mGy is a measure of radiation, mSv is a function of mGy depending on the biological effectiveness of radiation in free space on a given tissue, in this case human ovaries. The red color indicates that the 20 mSv/year threshold is reached. 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.

Location Influence on Radiation Shielding Requirement

The radiation experienced by space settlers depends a great deal on location. For example, on the surface of Mars or the Moon approximately 50% of the GCR is blocked by the body. Also, on Mars, there is some protection from the atmosphere. Furthermore, settlements can be located in caves or buried with local materials which are plentiful and relatively easy to move. Local materials can also be used by orbital space settlements when built co-orbiting with asteroids. This paper will focus on another strategy: placing settlements in low Earth orbit (LEO) to take advantage of the Earth's magnetic field and the Earth itself.

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 blocking GCR and from Earth's magnetic field. Very low inclinations, i.e., very close to 0, experience mush less radiation due to the shape of the magnetic field. See Table 5 below.

Table 2 contains the yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for circular equatorial orbits in both mSv/year and mGy/year 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 threshold and the shielding required to meet this threshold rises with altitude.

	600 km		700 km		800 km		900 km		1000 km	
tons/m^2	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy
1	14.2	5.2	25	10	109	60	238	135	409	234
2	14.1	4.9	18	5.9	39	9.8	158	72	115	23.7
3	12.1	4.1	14	4.7	23	6.4	36	8.9	55	12.4
4	9.5	3.2	11	3.6	14.7	4.3	20	5.3	28	7
5	6.9	2.3	7.8	2.5	9.5	2.8	11.9	3.3	15.5	4.1

Table 2: Yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for circular equatorial orbits in both mSv/year (human ovaries) and mGy/year. Rows are for 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 threshold. All calculations use OLTARIS.

Noting that at 600 km with a single ton of shielding the radiation expected, 14.2 mSv/yr, is well under the 20 mSv/yr threshold. We did additional calculations at 500 and 600 km using very small amounts of shielding. The results are in Table 3:

shielding	500 km		600 km	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	16.7	1.02	23.4	13.7
0.01	16.3	3.6	21.7	100
0.025	15.6	3.7	19.8	50.1
0.05	14.6	3.9	17.5	21.8
0.075	13.9	4	16.1	12.5
0.1	13.3	4	15	8.9

Table 3: Yearly radiation levels calculated for circular equatorial orbits at 500 and 600 km altitude. The rows are for 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. The columns are radiation levels at different altitudes and different measures. Note that even with essentially no shielding a 500 km orbit easily meets the 20 mSv/year threshold and the 600 km almost meets it as well. Red indicates that the level roughly meets our 20 mSv/year threshold. All calculations by OLTARIS.

Table 3 suggests that for settlements in very low equatorial orbits no shielding is required to meet the 20 mSv/year threshold. Of course, secondary radiation produced by the hull and interior materials may increase the radiation levels experienced but that requires detailed knowledge of hull materials and thickness and an understanding of the interior structures that is well beyond the scope of this pape. Fortunately, even with small amounts of shielding producing secondaries we are still below the 20 mSv/year threshold. There is, however, an interesting effect we can analyze.

The effect of secondary radiation can be seen in Table 4. Note that the small amount of shielding one might expect from settlement structure, atmosphere, interior buildings and so forth may actually increase the effective dose experienced with smaller levels of shielding but stays below the 20 mSv/year threshold and below the radiation experienced with no shielding.

shielding	600 km	
ton/m^2	mSv/yr	mGy/yr
~0	23.4	13.7
0.01	21.7	100
0.025	19.8	50.1
0.05	17.5	21.8
0.075	16.1	12.5
0.1	15	8.9
0.15	13.6	6.1
0.2	12.9	5.3
0.25	12.5	4.9
0.5	12.6	4.9
0.75	13.4	5.1
1	14.2	5.2
1.25	14.4	5.2
1.5	14.5	5.2
1.75	14.4	5.1
2	14.1	4.9

Table 4: Note the local minimum at 0.25 tons shielding and the local maximum at 1.5 tons with radiation increasing between the two. The minimum is caused by blocking protons and the maximum by unabsorbed GCR secondary radiation which causes more damage than the primary particles. The first column is tons of polyethylene shielding per square meter at a 600 km circular equatorial orbit. Red indicates that the level roughly meets our 20 mSv/year threshold. All calculations by OLTARIS.

Figure 1 illustrates the physics behind this effect.

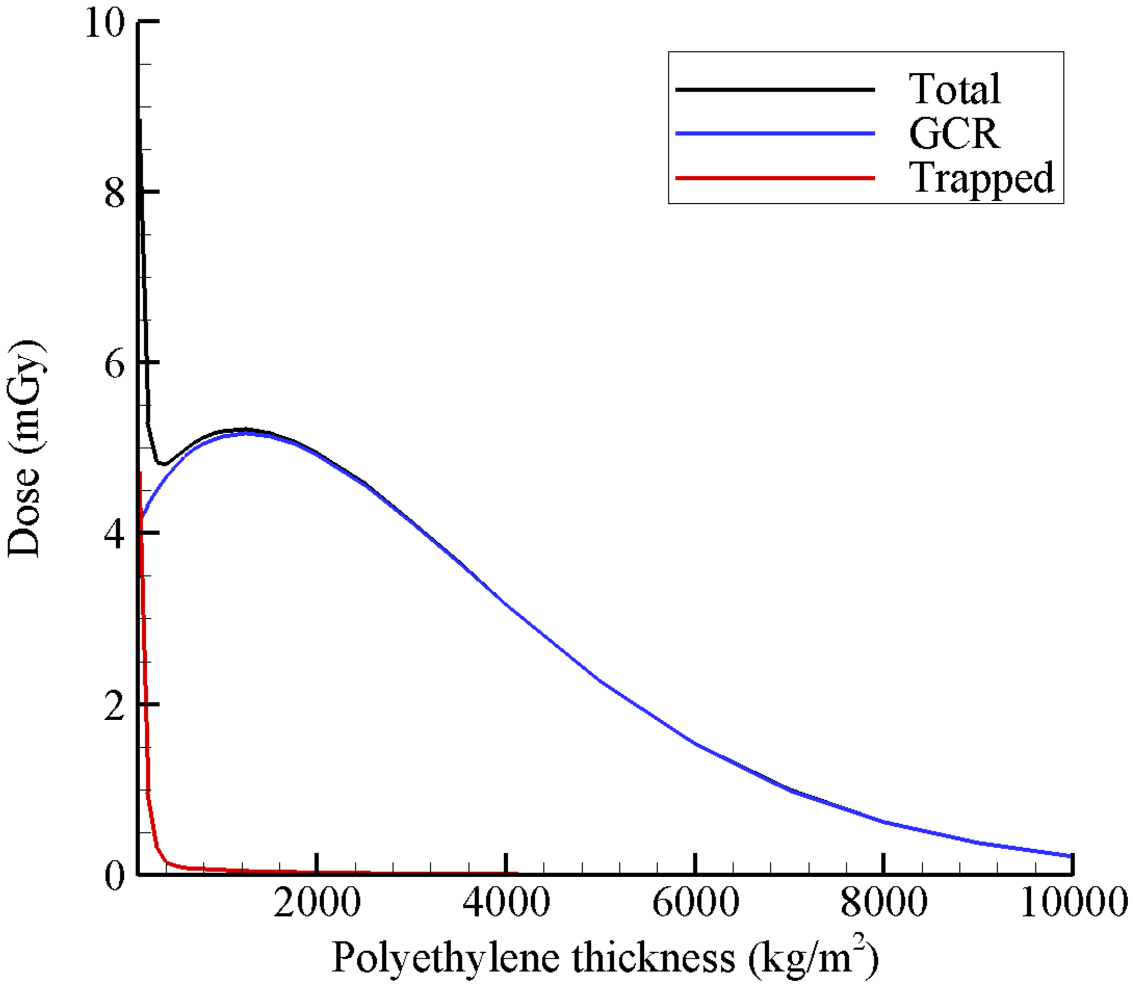


Figure 1: The trajectory was circular at 600 km and 0 degree inclination. The trapped proton component (red line on plot) is mainly lower energy protons that are stopped with little shielding. The dose profile from this part of the environment falls off rapidly with depth as one might expect.

The GCR component (blue line on plot) is high energy protons, alphas, 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 shield that produce secondary particles leading to an increase in exposure. You can see the dose increases until around 1,500 kg/m^2, and then gradually declines thereafter. This behavior is analogous to the so-called Pfotzer maximum observed in the Earth's atmosphere. [Slaba 2014]. Image credit NASA.

To understand the effect of inclination note that there is a region of high radiation near the equator called the South Atlantic Anomaly [Schimmerling] shown in Figure 2. The 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 threshold even at fairly small inclinations. This is because equatorial orbits bypass most of the South Atlantic Anomaly. Clearly, LEO settlements should be in equatorial orbits if at all possible.

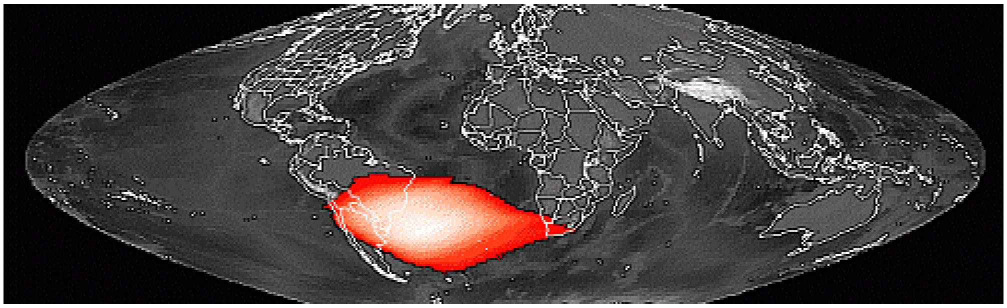


Figure 2: Red and white indicates the South Atlantic Anomaly. Note that equatorial orbits avoid most of it. Image credit NASA.

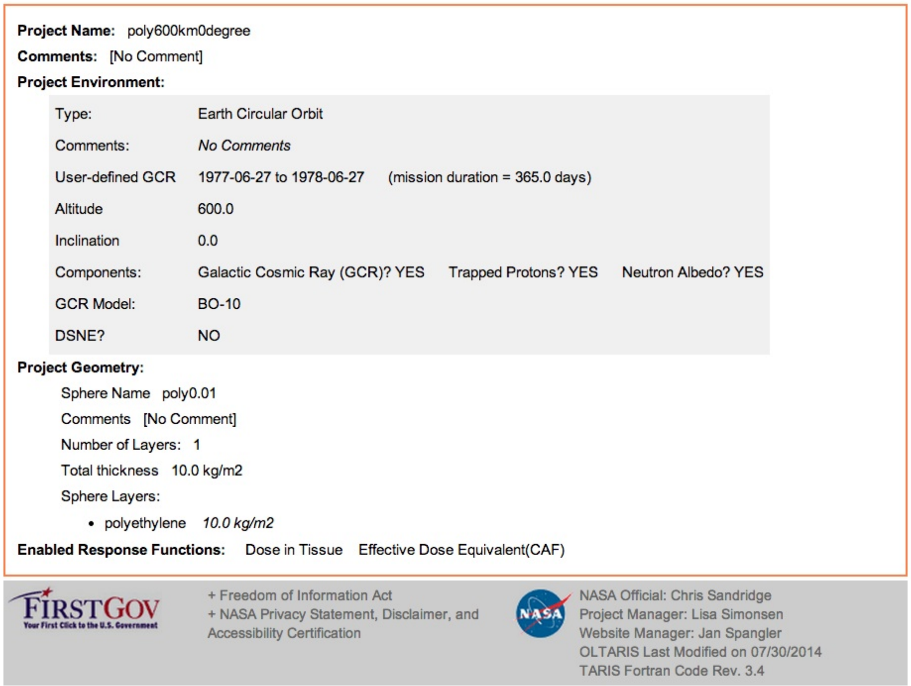
Mass (tons/m^2)	0° (mSv/yr)	15° (mSv/yr)	30° (mSv/yr)	45° (mSv/yr)	60° (mSv/yr)	75° (mSv/yr)	90° (mSv/yr)
0.25	14.6	262.8	636.0	424.1	345.0	335.5	334.0
0.5	12.1	112.1	253.5	178.2	164.0	168.7	170.3
1	13.2	43.4	88.7	79.1	90.3	100.2	102.7
2	14.0	21.6	36.7	45.5	58.9	66.4	68.3
3	12.6	16.4	25.1	33.2	42.4	47.1	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 shielding. The columns correspond to different orbital inclinations at a 600 km altitude. Red indicates that the level roughly meets our 20 mSv/year threshold. The levels reported here are for human tissue in general, not human ovaries as in the other tables. Thus, the levels are not directly comparable to other tables in this paper but the differences are. This measure is more optimistic as the ovaries are particularly vulnerable to radiation. Note that the other LEO tables use polyethylene and this uses water. All calculations by OLTARIS.

Method

All of the calculations in this paper were made with OLTARIS. Figure 3 indicates the parameters used for the LEO calculations (except Table 5). Only the altitude and material (the “sphere”) and the altitude were changed for each run. The model is human ovaries in the middle of a sphere of uniform materials.

Figure 4 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 mSv/yr columns always came from the human ovaries results. 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:

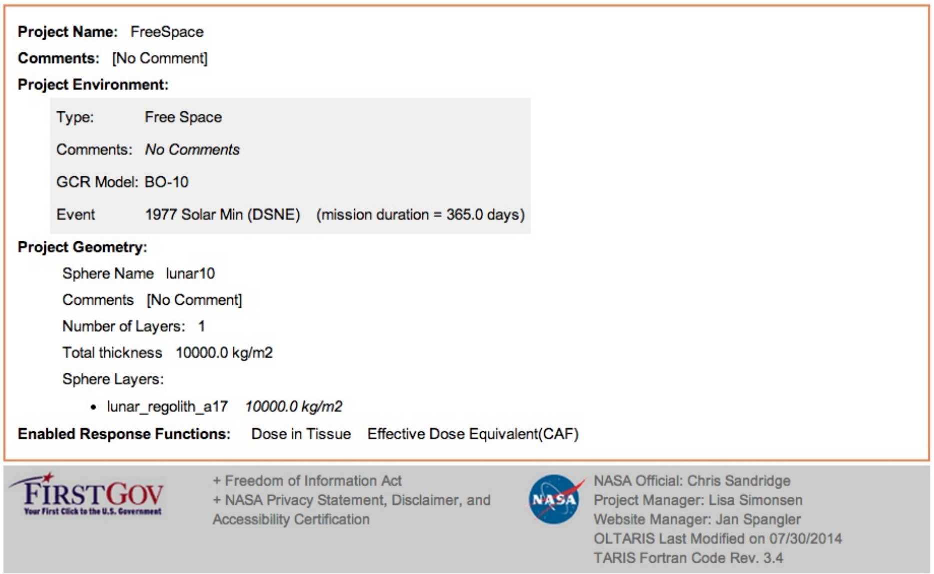
Sphere Name poly0.01
Comments [No Comment]
Number of Layers: 1
Total thickness 10.0 kg/m2
Sphere Layers:

- polyethylene *10.0 kg/m2*

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

NASA Official: Chris Sandridge
Project Manager: Lisa Simonsen
Website Manager: Jan Spangler
OLTARIS Last Modified on 07/30/2014
TARIS Fortran Code Rev. 3.4

Figure 3 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)

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TARIS Fortran Code Rev. 3.4

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

Radiation in space varies with time. All of these calculations used the same one year time period during the 1977 Solar Minimum, which is a conservative choice for GCR levels which tend to be high at solar minima. Most other time periods would be expected to generate lower radiation figures.

Discussion

The primary interest of the authors is in space settlement and these radiation shielding findings, should they stand up to further investigation, have strong implications for the easiest path to the first settlements and how we might spread throughout the solar system.

The result that no shielding material may be necessary for settlement in LEO equatorial orbit was surprising to the authors and has far reaching consequences because shielding above the Earth's magnetic field is about 90% of the mass of Kalpana One, a 3,000 person space settlement design [Globus 2007], and Kaplana One is designed to minimize shielding mass. Of course, the no-shielding result may be optimistic. While the 20 mSv/year limit may be sufficient to avoid premature sterility there may be more severe than expected problems with birth defects, cancer, cardiovascular problems, central nervous system problems and/or cataracts all of which can be affected by in-space radiation, although there is reason to believe ovaries are the most at risk. Those problems may not be sufficiently severe to deter a small fraction of Earth's population from moving into space settlements, and only a very small fraction of Earth's seven billion people are needed. The pull of space settlement can be very strong. For example, a recent call for volunteers for an extremely risky one-way Mars settlement plan received over 200,000 responses [Mars One 2014]. Moving from place to place on Earth often involves a significant increase in risk for a variety of reasons and people do it anyway. There is more to life than minimizing radiation exposure.

Also, no space settlements are likely to be built in the next few decades, and it is reasonable to expect that at least some of the problems expected from the levels of radiation found in space will become easily correctable on this time scale. For example, cataracts can be treated effectively today. Earlier cataract surgery than expected on Earth may be of minor importance compared to settling space for many. Also, the risks from space radiation may be minor compared to other risks. All this suggests that a threshold in the neighborhood of 20 mSv/year is adequate to allow settlement of the solar system.

If the threshold is 20 mSv/yr, then the assumption that space settlements have massive shielding requirements falls apart in LEO equatorial orbits. This makes it possible that launching most or even all of the mass from Earth will be less expensive than bringing lunar or asteroidal materials to LEO. Furthermore, the total quantity of materials necessary compared to settlements located near lunar and asteroidal materials is much, much smaller as radiation shielding is unnecessary and one can launch exactly what is needed rather than gathering bulk materials from the Moon or asteroids. Thus, settlements located in LEO equatorial orbits may require far less mass than in any other orbit. Compared to the 1970s studies, this eliminates the entire extraterrestrial mining, processing and manufacturing infrastructure assumed to be necessary to build the first orbital settlements, although this infrastructure is highly desirable later on as we spread throughout the solar system and settlements in LEO may be a lucrative market for asteroidal and lunar materials. In any case, making extraterrestrial mining out of the requirements for the first settlement allows a much more incremental approach to settling the solar system.

With no extra shielding beyond the structure, furnishings and atmosphere, a settlement in LEO may be vulnerable to particularly large solar flares. Fortunately, at the highest flux levels these are relatively short, usually hours, and dangerous ones are rare [Cucinotta 2012]. In a settlement such as Kalpana One with a low-g cylindrical swimming pool around the axis of rotation the pool can be used as a solar storm shelter, I.e., on the rare occasions that a solar storm threatens everyone has to go swimming 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!

Of course, settlements in LEO will be subject to atmospheric drag and without reboost will eventually enter the atmosphere and impact the ground. 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 3,000 person 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[5].

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

This activity does require a great deal of energy, but the dominant use of energy on orbital settlements such as Kalpana One is for intensive agriculture and reboost can occur during periods of darkness needed for plant health. Heavy objects in the 500-600 km equatorial orbits take centuries to millennia to deorbit if abandoned, leaving ample time to deal with any such event. For example, using the Orbital Lifetime Calculator[6] assuming a very lightweight 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 and over 1,670 years at 600 km.

Preliminary calculations put the total mass of Kalpana One (a 325m long, 250 m radius cylindrical settlement) at about a half million tons assuming no shielding mass[7]. This would require roughly 10,000 launches of a Falcon Heavy (due to launch in 2015) [SpaceX 2014], or 1,000 launches of the Sea Dragon design of the 1960s [Space Technology Laboratories 1963]. As construction might be reasonably expected to take around two decades, this amounts to 50 - 500 launches a year, more or less in the range of the highest launch rates in the past (around 175/year).

While the high end is much higher than current launch rates, a vigorous space tourism market could generate demand on this order or even significantly greater [Globus 2012]. This opens up the possibility of a smooth path to the first settlement starting with small orbital space stations (for example, the International Space Station) and hotels followed by more and larger facilities as prices drop and demand grows. This might be followed by orbital retirement homes maintained at low g-levels to accommodate an infirm clientele. Then small settlements might be built, perhaps in a dumbbell configuration that in higher orbits would require large amounts of radiation shielding due to the large hull surface area. All this would lead up to small city-sized settlements like Kalpana One in LEO.

The superiority of asteroidal materials, heavy in carbon compounds and water, to lunar materials for free space settlement radiation shielding has implications to the paths for growth as we settle the solar system. Even in cis-lunar space the accessibility of some Near Earth Objects (NEOs) and the superior radiation shielding characteristics of asteroidal materials may make retrieved asteroids the preferred material source for cis-lunar radiation shielding above the Van Allen Belts. The current project to retrieve a small asteroid would be of great value for this path. For settlement of heliocentric orbits the obvious approach is to build settlements co-orbiting with asteroids that supply the materials for the settlement. In the long term settlements built co-orbiting with asteroids make the entire solar system available for settlement. This also means that generation ships to nearby stars do not need a habitable planet as their destination; just some space rocks will do.

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

[7] Kalpana One has a mass of about five million tons with six tons of shielding per square meter, the amount of polyethylene need outside of Earth's magnetic field.

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. The data are not good enough for definitive conclusions.

First, it appears that 20 mSv/year is a reasonable threshold for space settlement inhabitants. This is much higher than the average background radiation experienced by most people on Earth, but there are many parts of the world where background radiation approaches or even exceeds this level.

Second, given a 20 mSv/year limit, space settlements in LEO circular equatorial orbits may not require any shielding at all. This has strong implications for the location of the first orbital space settlement which, contrary to previous belief, may be easier to build in LEO using only launch from Earth than depending on extraterrestrial mining, processing and manufacture. This is because of the shielding provided by Earth’s magnetic field and by the Earth itself. Of course, a settlement in LEO is better positioned for commerce with Earth than settlements in higher orbits or on the Moon or Mars. Tourism is an obvious candidate, but space solar power stations, manufacturing and research using the unique environment of space may also provide income.

Finally, asteroidal materials -- from the right kinds of asteroids -- are superior to lunar regolith for radiation shielding. This may mean that retrieving asteroids into Earth orbit may be competitive with launching regolith from the Moon for radiation shielding of settlements in cis-lunar space. Furthermore, asteroids are a ready source of materials for settlements in heliocentric orbits.

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