Requirements for Future Generation Space Habitats

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While the International Space Station has a mass in the 480-tonne range, and requires propulsion only to raise its orbit to maintain altitude, and for minimum movements to avoid space debris, future generation space habitats will require more extensive propulsion. In this presentation we examine the needs of a potential class of more massive space habitats. For our example, we propose a set of space stations having a standardized format including a sparse ring configuration, rotational gravity, and substantial dedicated shielding from cosmic radiation. These larger habitats, with masses in the 5,000-tonne range, will most likely be constructed in low Earth orbit for reasons of cost and schedule. But they may be needed in Lunar orbit, or at a Lagrange point, or Mars orbit, or even as an Aldrin cycler. The propulsion systems to get them to any of those destinations will require levels of energy well beyond any systems previously developed. We will discuss the likely requirements and alternatives for these systems.

I. Introduction

If our civilization is to send people out into our Solar System for more extended stays, and allow inclusion of a broader selection of people without needing extensive astronaut selection and training, we will need a *new generation of space habitats*. And these habitats will need to be deployed in multiple locations. A preferred approach is to design the habitats at all locations to a standard configuration, to reduce development cost and schedule, and for standardized maintenance and operation.

These longer-term habitats will need to provide *rotational gravity*. After nearly 19 years of constant staffing of the International Space Station, it has become clear that a 0 G environment is damaging through loss of muscle and bone mass, vision problems, migration of spinal and brain fluid, and further problems. Efforts with diet supplements and punishing exercise regimens have had only limited success. Astronauts and cosmonauts upon return to Earth after six months are hoisted out of their capsule and laid out on lounges, unable to walk. They are not allowed to sit up and drive a vehicle for 21 days. And the one-year experiment with the Kelly twin was unexpectedly grueling, with a longer recovery after returning to Earth. Only rotational gravity can solve these problems in the foreseeable future.

The longer-term habitats will also need to provide substantial *dedicated shielding* from continuous cosmic radiation and bursts of solar radiation. While the ISS benefits from protection from cosmic radiation by both the Earth's mass on one hemisphere and the Earth's magnetic field on the other, habitats beyond low Earth orbit will be unprotected. There is much uncertainty about radiation dosage limits, but NASA specialists have been deeply concerned that a round trip to Mars, for example, would exceed safe limits if conducted in a habitat with no dedicated shielding. If shielding is provided that reduces cosmic radiation dosage by a factor of 5, then crews on a two-year mission would incur a radiation dose equivalent to only a 4.8-month unprotected mission.

Increased mass is the natural result of these improvements in rotational gravity and radiation shielding. In the following sections, we will examine the delta-Vs required to *transfer the habitats* from low Earth orbit where they are constructed to other locations in the Solar System where they are needed. Then we will look at the mass of a baseline example habitat and the resulting propulsive energy required to transfer it to key locations.

II. Potential Habitat Locations and Required Delta-Vs

Multiple locations around the Solar System might be considered for habitats, including these examples:

- Low Earth orbit

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- Lunar orbit
- Earth-Moon Lagrange points
- Sun-Earth Lagrange points
- Mars orbit
- Earth-Mars Aldrin cycler
- Accompanying an asteroid or comet

Clearly, low Earth orbit is a negligible case, with no propulsion required. For this paper, we will focus on lunar orbit and Mars orbit. All the human exploration programs around the world today are strongly focused on the Moon and Mars. As they progress, they may well discover that bases on the surface are inadequate for long-term occupation. For example, the low 1/6 G gravity on the Moon may be damaging enough to long-term inhabitants that they can not return to Earth, which requires challenging rocket blast-offs and re-entry. As a result, lunar colonists actually may be limited to short visits on the surface, with longer breaks in the orbital habitat. On Mars, the much greater distance may substantially delay the arrival or successful function of 'earth'-moving equipment on the surface. That will delay the radiation shielding of surface habitats with layers of regolith. As a result, Mars colonists may also spend short visits on the surface, with longer breaks in the orbital habitat.

The change in velocity, or delta-v, required for transfer of a habitat from low Earth orbit to low lunar orbit is 4.04 kilometers per second for high-acceleration propulsion, but for low-acceleration propulsion, without the Oberth effect, it is *8.0 km/s,* according to the Wikipedia article https://en.wikipedia.org/wiki/Delta-v_budget.

The delta-v required for transfer of a habitat from low Earth orbit to Mars equatorial orbit is about 6.6 km/s using high-acceleration propulsion, also according to the article above. For low-acceleration propulsion, without the Oberth effect, it may be as much as *13.0 km/s*.

III. Historical Space Habitat Concepts with Rotational Gravity

Enormous mass and resulting enormous cost have always been the major barriers to building space habitats with rotational gravity. There have been numerous proposals over the years, starting surprisingly early. Here are some selected examples:

- Hermann Noordung, ring station, 1928
- Wernher von Braun, ring station, 1956 [1]
- Willy Ley, ring station, 1958 [2]
- Arthur C Clarke, ring station in book *2001: A Space Odyssey*, 1968
- Stanley Kubrick, ring station in movie *2001: A Space Odyssey*, 1968
- Gerard O'Neill, tandem cylinders, 1976 [4]
- Al Globus, Kalpana cylinder, 2006, 2010

All of these proposals required constructing a very large and massive monolithic pressurized volume from hundreds or thousands of complex pieces, probably using large numbers of workers in space suits. To cite just two examples, consider the von Braun wheel and the O'Neill cylinders.

One preferred configuration of the *von Braun wheel* had a major diameter of the torus of 2 km, and a minor diameter of 100 meters. That is equivalent to a curved fuselage with a length of 6.28 km, or 89 times the length of a 747-400ER, and a cross-section area about 256 times that of the 747. The resulting volume is 22,880 times that of the 747 fuselage. If mass is roughly proportional to volume, which is usually true for pressure vessels, then the torus would have a mass of about 4.5 million tonnes. The complete station might be *6 million tonnes*.

For the *O'Neill cylinders*, a preferred configuration was two tandem cylinders, rotating in opposite directions to reduce gyroscopic effects. Each cylinder was 6.4 km in diameter and 32 km long. Although the air was reduced to half density by reducing the nitrogen from 80% to only 30%, the mass of the air alone would be *1.2 billion tonnes*. And the complete station would be vastly more.

These rotating stations have always been far out of reach of our technology in the past, the present, and also for the foreseeable future.

IV. Recent Space Habitat Concepts with Rotational Gravity

In more recent years, some habitat concepts have been developed that use smaller rings, and consider fractional G rotational gravity and/or fractional time for inhabitants in the rotational gravity. Some examples are:

- Mark Holderman, NASA, Nautilus-x, 2011

- Andy Weir, Hermes spacecraft, in book *The Martian*, 2011
- Ridley Scott, Hermes spacecraft, in movie *The Martian*, 2015
- Torin Clark, UC Boulder, rotating prone platform, 2019

These designs are much more promising. However, they are limited by a lack of any research results on what fractional G level or fraction of each day will maintain good health for people during two years or more of residence in the habitat. For now, the only level we can be certain of is 1 G all the time. As a result, research results would be very valuable for future designs.

V. The ModRing Space Habitat with Rotational Gravity and Shielding

In order to determine a practical mass for a space habitat with rotational gravity and dedicated radiation shielding, we have developed a habitat concept called the Modular Ring, or ModRing, that uses a set of design decisions in order to naturally optimize the configuration. We propose these design decisions as potentially the best way forward. Each decision is described in more detail below.

The probable limit of rotation rate for avoiding nausea and dizziness is *one revolution per 30 seconds*, based on the best (but somewhat limited) research data. To achieve 1G at this angular rate, the habitat requires a *diameter of nearly 500 meters*, which we adopt for this design.

A. Modular Habitable Volumes

The ModRing overcomes the mass barrier by dividing the habitat volume into multiple habitat modules of spacious but practical scale. All those earlier concepts were based on a single very large monolithic pressurized volume, in the shape of a torus or cylinder. That forced the pressure vessel to be constructed in space, from hundreds or thousands of pieces, probably by workers in space suits. No residents could move in until the entire pressurized volume was completed and tested and pressurized with breathable atmosphere.

The ModRing pressurized habitat volume is divided into the largest *modules* that are practical to launch as completed units. All module construction is done economically on the ground, and only fully equipped and fully tested modules are launched to orbit. Based on an analysis of larger launch vehicles expected to be available within a few years, we have selected a module size of 6.2 meters in diameter by 25 meters long. Modules would have a projected launch mass of 41 tonnes, also based on expected launch vehicles. Specifically, they are sized for the smallest of the coming large launchers, the Blue Origin New Glenn, but with a stretched fairing. Larger vehicles, such as the NASA SLS and the SpaceX Super Heavy, could also be used.

The modules would be constructed similar to ISS habitat modules, and would be configured much like an airliner fuselage, with lengthwise upper and lower decks. There would be a double wall hull, however, with an internal pressure shell and an external unpressurized shell to contain the radiation shielding. The internal shell diameter would be 4.6 meters, much like a Boeing 767 airliner.

Each end of the habitat modules would have a 1.5-meter pressure door, which could be sealed in emergencies. All interfaces would be standardized, to allow modules from multiple manufacturers or countries to interoperate seamlessly.

B. Sparse Construction

These modules are attached to a very lightweight *sparse structure*, somewhat inspired by the construction of the London Eye and similar very large observation wheels. The largest of these wheels is over 200 meters in diameter. They consist of a light structural ring with passenger pods, many radial tension cables, and a central hub. These are exactly what we use in the ModRing concept. In order to deal with the human need for gravity in space, we must learn to embrace sparse structure, and make it work for us.

The baseline ModRing configuration includes a 500-meter diameter ring, with 4 pairs of habitation modules spaced equally around the ring, and another pair on the axis, forming a hub. The hub also includes two structural hub disks for attaching the radial tension cables, and two docking bays and docking ports. Supply vehicles would dock while rotating on their roll axis to match the 30-second rotation period of the ModRing.

Access to the habitation modules from the hub is provided by dual sets of 4 radial access tubes, equipped with electric elevators, and by dual perimeter access tubes around the ring, equipped with electric shuttle carts. The radial tubes have dual internal linear toothed gears for the elevators to climb, and the perimeter tubes have an internal roadbed for the shuttle carts to drive on.

In the future, as larger crews need to be accommodated, this design can readily extend to 12 pairs of habitat modules around the ring, or even 12 or more triples of habitats, as shown in Figs. (1, 2).

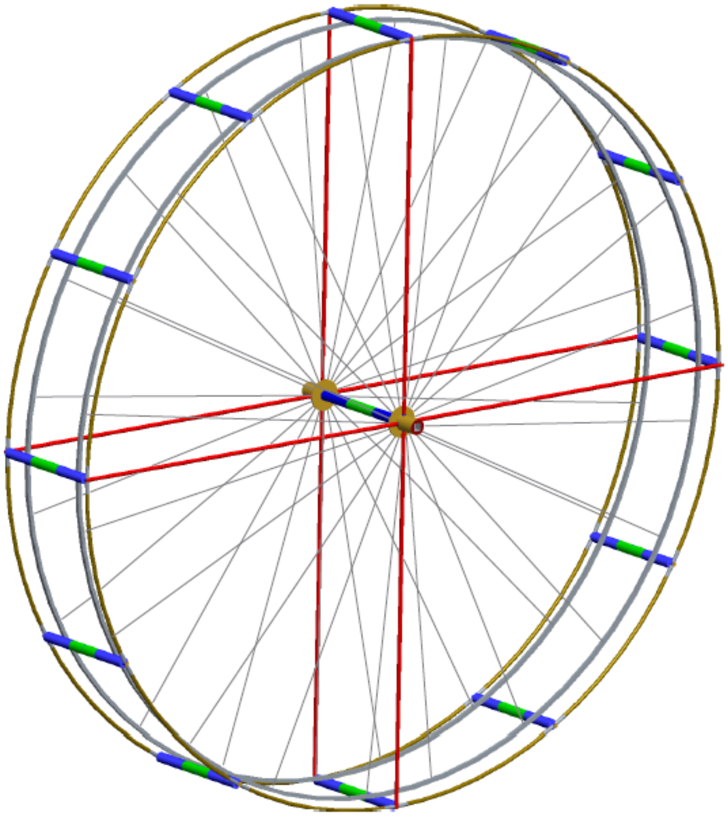

Fig. 1 Extended ModRing with 12 triples of habitation modules on the ring.

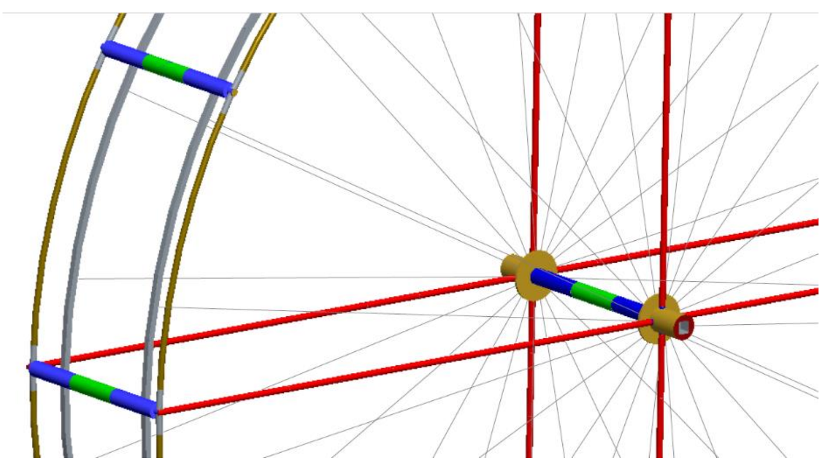

Fig 2 Closer view of extended ModRing with 12 triples on the ring.

C. Repetitive Use of a Few Key Types of Elements

For both economy of production on the ground and efficiency of assembly in space, the ModRing uses a few key types of elements, connected repetitively to produce large structures on orbit. The ModRing is constructed of the following elements:

- Two structural rings -- Gray
    - Each constructed of 60 straight 25m segments
    - Triangular cross section, 3 meters on each face
- Two perimeter ring access tubes with shuttle carts -- Bronze
    - Each constructed of 60 straight 25m segments
    - Circular cross section, 2.6 meters diameter
    - Three lengthwise external ribs for strength
    - Internal road bed for shuttle carts
- Eight radial access tubes with elevators -- Red
    - Each constructed of 10 straight 25m segments
    - Circular cross section, 2.6 meters diameter
    - Three lengthwise external ribs for strength
    - Internal linear gears for elevators to climb
- 8 habitat modules on the ring -- Blue, Green
- Two habitat modules on the axis -- Blue, Green
- 360 tension cables (Only 40 shown) -- Gray
- Two structural hub disks at the ends of the axis habitat modules -- Tan
- Two docking bays beyond the ends of the (hollow) hub disks -- Tan
    - Each half length of habitat module, with docking port
- Solar photovoltaic arrays as needed on one face -- Not shown
    - Space for up to 10 Megawatts
- Various systems for operation -- Not shown
    - Including automated stability and balance system

For launching most of the elements, several of them will fit within the 25-meter length of the fairing. Initial estimates are that each launch to low Earth orbit can deliver 1 habitat module, or 2 docking bays, or 4 access tube segments, or 6 structural ring segments, or 10 tension cables.

D. Construction by Semi-Autonomous Assembly Tugs

The ModRing overcomes the construction barrier by being designed as many standardized repetitive units of a few types of elements and by utilizing a few semi-autonomous *Assembly Tug* spacecraft to connect all the pieces as they arrive on orbit. All the external specs of the habitat modules are thoroughly standardized, including size, fasteners, and provisions for electrical power, communication lines, make-up water, waste lines, and more. This allows simplified assembly.

The Assembly Tug spacecraft and a *Tool Shed* with a few complex tools for assembling the modules are launched first. As each payload arrives on orbit, the Tugs select a tool, meet the payload, grapple it, and then connect the newly-arrived pieces. Three Tugs are required for handling a habitat module: one Tug to grasp each end and position it, and a third Tug to connect and attach it to the ring.

Standardizing a few types of modules and using automated assembly is crucial for enabling such a large structure.

E. Radiation Shielding by Polyethylene Pellets

In earlier designs, the need for serious radiation shielding frequently involved ideas such as thick layers of regolith launched from the shallower gravity well of the Moon. That also drove excessive mass, as well as major additional challenges for a Lunar infrastructure. As a result, dedicated radiation shielding has not been provided for general living spaces in the ISS or other habitats.

The ModRing overcomes the shielding barrier by providing compartments between the double hulls of the habitat modules, filled with *polyethylene pellets*. The Assembly Tugs will fill these compartments using dedicated tools. Polyethylene is the preferred shielding material for US Navy nuclear submarine reactors and nuclear aircraft carrier reactors. It has kept generations of nuclear vessel crews safe. It is also used around the sleeping spaces in the US side of the ISS. Compared to water, it has the advantages that it will not freeze, or leak, or evaporate. The pellets, perhaps 80mm diameter spheres, are easy for the Assembly Tugs to handle and to meter them into the shielding compartments. Of course, the disadvantage is that they cannot also serve as emergency drinking water.

If the ModRing is to allow 2 years or more of safe habitation in space, it must provide radiation shielding for Galactic Cosmic Rays to reduce effective dosage to about 1/5 of the unshielded rate. Then a 24-month stay on board will result in a cumulative dosage similar to a 4.8-month stay with no shielding.

Using the recent results from the ESA ALTEA instrument [6] on board the ISS, which took data only at high-latitude points to avoid shielding effects of Earth's magnetosphere, and Simonsen et al 1997, we estimate that about 0.5 meters of polyethylene [7] would be needed in addition to shielding from structure. If the shielding pellets are spheres, perhaps 80mm diameter, they would have a random packing density of 0.63, when filled without individual placement. This yields a required shielding compartment depth of 0.8 meters. This depth adds a shielding mass of 203 tonnes to the mass of each unshielded habitat module, a major but acceptable mass penalty.

While the radial and perimeter ring access tubes will not be shielded, the shuttle carts and elevators that travel in them would be shielded with thinner 0.2m solid polyethylene cabins, to reduce effective dose rates to about 1/3 the unshielded rate, including shielding from structure.

F. Redundancy on Multiple Levels for Safety

Longer residence time in space naturally leads to increased chances for emergencies. In order to deal with potential emergencies, the ModRing employs *dual redundancy* in many aspects. For example, habitation modules are mounted in pairs, with sealable doors to provide a safe haven if one module has an emergency. Also, the long perimeter access tubes could be a weakness for safety. If one perimeter tube gets breached, it may need to be sealed off. Then the second perimeter tube is critical for safety, the only way out for the crew. Likewise, if one of the hub modules, which handle all freight deliveries, potentially including anhydrous ammonia coolant and toxic hypergolic fuel for thrusters, should be breached or made toxic, then the other module could be sealed off from it, and would be their only way out.

Two sealable habitation modules at each cluster, two perimeter access tubes, two sets of elevators, two docking bays and docking ports, will make the habitat much more robust to successfully manage a bad day.

G. Resulting Mass of Baseline ModRing

Initial calculations of the mass of the baseline ModRing with four pairs of habitation modules on the ring are based on the estimated masses of each type of repetitive elements, and the numbers of each element. These lead to a projected mass of 4,800 tonnes.

For our propulsion calculations, we will use an estimated mass of *5,000 tonnes* for this example of a next-generation space habitat with 1G rotational gravity and substantial dedicated radiation shielding.

VI. Propulsion Energy Required

The propulsion energy required to transfer the habitat itself from low Earth orbit to a low orbit around the Moon or an equatorial orbit around Mars is readily calculated from the known delta-v for each transfer (8.0 km/s and up to 13.0 km/s), together with the estimated mass of the habitat, 5,000 tonnes. Additional energy will also be required to transfer the mass of the required propulsion system. And allowance must be made for efficiency of the propulsion system.

VII. Alternative Propulsion Methods

The known set of propulsion methods for transfer around the Solar System includes chemical rockets, solar electric, solar thermal, nuclear thermal, and nuclear electric. Here we will examine the practicality of each of these methods.

Chemical rockets to transfer such a massive habitat are impracticably large. The mass ratio for these delta-vs lead to Earth departure stages that are much more massive than the 5,000-tonne habitat. Because the most capable launchers on the horizon, the NASA SLS and SpaceX Super Heavy, are designed to launch only about 100 to 250 tonnes to low Earth orbit, there is no practical way to launch a large enough chemical rocket for these missions.

Solar thermal and nuclear thermal can achieve higher exhaust velocity and specific impulse through use of hydrogen as the propellant. The low mass of hydrogen yields higher velocity for the same temperature, compared to exhaust of water vapor and carbon dioxide from chemical rockets. However, the most optimistic improvements still require a mass ratio that is far too large to be practical.

Solar electric propulsion, SEP, and *nuclear electric propulsion*, NEP, appear to be the only potential choices. The ion exhaust from SEP and NEP systems are accelerated to far higher velocities by electromagnetic fields than any of the other alternatives, leading to far higher specific impulse ratings.

An *SEP system* would be limited by the size of solar arrays that could be employed. For purposes of estimating, we consider a 2 MW array to be near the maximum credible power. In comparison, the large solar array on the ISS is rated at 250 kW when new. This is the largest array ever deployed in space. Clearly, a 2 MW array would be a major challenge. However, the area of one face of the ModRing is estimated to provide 9 MW, so the SEP array would require less than that area. A second comparison is the Power and Propulsion Element under development for the Lunar Gateway. It is expected to have an SEP system and a 50+kW solar array, only 2.5 percent of the 2 MW system. That SEP system is to provide about 2.4 newtons of thrust from 4 Hall thrusters when consuming 53.2 kW. Scaling it up to 2 MW yields a thrust of about 90 newtons using an array of 150 Hall thrusters.

Based on a power source of 2 MW and a thrust of 90 N, and the required delta-v of 8.0 km/s for the lunar transfer and 13.0 km/s for the Mars transfer, the SEP system would need to run for *14.1 years* for the lunar transfer and *22.9 years* for the Mars transfer.

An *NEP system* would be limited by the size of its nuclear reactor and electric generating subsystem. For purposes of estimation, we will make the initial estimate that the NEP system will also provide 2 MW of electrical power. Then the NEP system would also need to run for *14.1 years* for the lunar transfer and *22.9 years* for the Mars transfer.

VIII. Preferred Propulsion System

Either of the *solar electric* or *nuclear electric* propulsion systems would be the only possible choices for these missions. They would need to be far larger than any such systems ever deployed or even prototyped. And they would need to run for several years for each mission. Other known propulsion systems would not be practical.

IX. Practicality of Transfer to Lunar or Mars Orbit

The results above suggest that transfer of even a sparse-construction 5,000-tonne space habitat from low Earth orbit to Lunar orbit or Mars orbit is not likely to be practical. The large power requirements lead to both very large solar arrays and very numerous ion propulsion units for solar electric propulsion. For nuclear electric propulsion, it leads to a very large reactor and again very numerous ion propulsion units. As a result, it may be necessary to transfer individual habitation modules and groups of other elements using smaller electric propulsion systems. This will require numerous propulsion systems, and will incur increased complexity of assembly at far more remote locations.

X. Conclusion

After many years of innovative concepts for space habitats with rotational gravity and/or substantial radiation shielding that were all far too massive and costly to be within reach, we have demonstrated a configuration that appears to be practical. This concept, the Modular Ring or ModRing, could be built with a mass starting in the 5,000-tonne range. For comparison, selected earlier concepts were shown to have masses in the range of millions of tonnes or even billions of tonnes.

The ModRing combines the key design choices of modular habitable volumes, sparse construction, repetitive use of few key types of elements, assembly by semi-autonomous tugs, radiation shielding by polyethylene pellets, and redundancy on multiple levels for safety. The result in low Earth orbit is the first practical habitat with 1 G rotational gravity and substantial dedicated radiation shielding.

However, the desired ability to assemble standardized habitats in low Earth orbit and transfer them to other needed locations in the Solar System, such as lunar polar orbit or Mars equatorial orbit, is more problematic. The best potential propulsion systems, solar electric and nuclear electric, are barely adequate, even using the largest credible sizes of these systems. In practice, it may be necessary to transfer individual habitation modules and groups of other elements using SEP or NEP systems, and then assemble the habitat at the final location.

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References

[1] Von Braun, W., *Space Frontier*, revised edition, Holt, Rinehart and Winston, New York, 1971.
[2] Ley, W., *Space Stations*, Guild Press, New York, 1958.
[3] Levitt, I. M, *Target for Tomorrow: Space Travel of the Future*, Fleet Publishing, New York, 1959.
[4] O'Neill, G., *The High Frontier: Human Colonies in Space*, 1st ed., William Morrow & Co, New York, 1976.
[5] Simonsen, L., *Radiation Protection for Human Missions to the Moon and Mars*, NASA Technical Information Service, 1991.
[6] Narici, L., Casolino, M., Di Fino, L., Larosa, M., Picozza, P., Rizzo, A., and Zaconte, V., "Performances of Kevlar and Polyethylene as Radiation Shielding On-Board the International Space Station in High Latitude Radiation Environment," Nature, Scientific Reports 7, Article number 1644, 2017.
https://www.nature.com/articles/s41598-017-01707-2
[7] Rapp, D., "Radiation Effects and Shielding Requirements in Human Missions to the Moon and Mars," page 52, Mars, The International Journal of Mars Science and Exploration [online journal], Mars 2, 46-71, 2006.
doi: 10.1555/mars.2006.004
www.marsjournal.org/contents/2006/0004/