# Reducing Cost by Extending Crew Stay for Missions to the Moon and Mars

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**There are a large number of strategies for reducing overall mission cost for crewed missions. An overview of some of these approaches is considered. The specific focus of this paper is how cost fcould be reduced by extending crew stay on the Moon and Mars. By so doing, the transportation cost for rotating crew can be reduced while also reducing the risk of loss of crew.**

**We propose the use of the Earth Return Option where biomedical criteria indicate whether crew would need to return at the upcoming Earth return window or if they can choose to extend their stay until the following window. This could be done by ensuring that they have sufficient supplies, maintaining reliable life support systems, protecting from radiation and the effects of micro and hypogravity, and if possible, selecting crew whose social status allows for extended stays. We identify water-bearing supplies as a convenient way of reducing radiation exposure while in transit to Mars and regolith piled on top of habitats while on the surface of the Moon or Mars. While there, we propose the use of a centrifuge within a shielded habitat for several hours a day. The authors found that we could successfully conduct a variety of sedentary activities while spinning at the rate that would provide 1 g on the Moon.**

**Finally, we suggest that any crew on a mission exceeding two years or so would ideally not have dependent children or a spouse back on Earth. We believe that the ideal initial crew may be couples without dependent children. We conclude that, by utilizing the interventions that this paper suggests, crew stay can be extended resulting in an overall lower mission cost and risk.**

## Nomenclature

| | | |
|---|---|---|
| *COTS* | = | *Commercial off-the-shelf* |
| *EDL* | = | *Entry, descent, and landing* |
| *GCR* | = | *Galactic cosmic rays* |
| *ISRU* | = | *In-situ resource utilization* |
| *ISS* | = | *International Space Station* |
| *mSv* | = | *Millisieverts* |
| *NASA* | = | *National Aeronautics and Space Administration* |
| *RPM* | = | *Rotations per minute* |
| *RASC-AL* | = | *Revolutionary Aerospace Systems Concepts - Academic Linkages* |

## I. Introduction

In the 2015 movie, *The Martian*, astronaut Mark Watney finds himself stranded on Mars after his crew had to cut their mission short accidentally leaving him behind. Lacking the necessary resources to survive for very long, he uses his ingenuity to survive until a rescue mission is able to arrive.

Whereas the challenges portrayed made for an exciting movie, in practice, we may well want to plan for the crew to have the option of staying for extended periods of time. Not only would it give them a measure of safety but extending crew stay could be a key strategy for reducing mission cost.

Plans are under way for the establishments of off-Earth bases which could be developed by governments, privately, or some combination thereof [Pittman 2014]. But if those developments are to be sustainable in the long run, the cost of missions will need to be dramatically reduced.

## II. Overview of Methods for Reducing Cost for Human Missions to the Moon and Mars

Ultimately, cost reduction is not a simple uni-dimensional process, such as using composite structures or providing for extended stays. While this paper focuses on the extended stay option, this is one of many approaches that can be used to dramatically drive down the cost of human missions to the Moon and Mars. Reducing cost is a far more complex, multi-faceted process that involves multiple elements working together. A summary of several of the most important elements in this systems process is given in Table 1 and individual approaches are summarized below.

**A. Reducing Transportation Cost.** Currently, the cost of putting things on the surface of the Moon or Mars is far too expensive for meeting the objectives of establishing permanent, growing bases / settlements. There are 4 broad approaches, which, when applied together, can achieve this cost reduction.

**(1) Reducing launch cost.** There are a number of approaches being pursued at the present time. These include:

- Low-cost expendable launch systems
- Reusable launch systems
- Air launch systems

If any of these approaches succeed in substantially reducing cost, this could go far towards making lunar or Martian development cost-effective and sustainable.

| Method | Applicable to | | | |
|---|---|---|---|---|
| | **Small Lunar mission** | **Large Lunar Colony** | **Small Mars Mission** | **Large Mars Colony** |
| **Reduced Transportation cost** | | | | |
| **Extended stay** | **Yes** | **Yes** | **Yes** | **Yes** |
| **Indigenous Resources ($O_2$)** | Possible | Yes | Possible | Yes |
| **Economies of Scale** | No | Yes | Some | Yes |
| **New Technologies** | Possible | Probable | Possible | Probable |
| **Reduced Acquisition Cost** | | | | |
| **Use COTS Equipment** | No | Yes | No | Yes |
| **Cost Sharing** | Some | Yes | Some | Yes |
| **Income Generation (= Creating Negative Cost)** | Some | Very Large | Yes | Large |
| **Reduced Operations Cost** | | | | |
| **Eliminate Earth Control** | Some | Yes | Some | Some |

**Table 1.** *Summary of Major Methods for Reducing Cost for Human Missions to the Moon and Mars. (from Wertz, et al. [2016])*

**(2) Using lunar/Martian resources for propellant**. It appears that both the Moon and Mars have water ice. If this could be harvested and processed into propellant it could substantially reduce the amount of the mass needed to be launched from Earth. At a minimum, this propellant would be particularly beneficial for the last leg, namely, from the surface of the Moon or Mars to their low orbits and back as well when returning to Earth.

**(3) Extending the stay duration**. While this approach does not reduce transportation cost per kg, it does reduce the overall transportation cost by significantly reducing the number of trips required, as discussed elsewhere in this paper.

**(4) Economies of Scale.** As bases grow to colonies with a large population, thousands of tons of equipment, material, and people will need to be shipped from Earth. This corresponds to a very large number of launches which can provide a cost reduction factor of about three due to economies of scale.

**B. Reduce Acquisition Cost**

**(1) Use COTS Equipment**. As shielded bases are established and launch costs are reduced, commercial-off-the-shelf hardware can be shipped to the bases where the crew could use them. Extensive testing and over-engineered design of hardware would not be necessary.

**(2) Cost Sharing.** Different users (e.g. government, commercial) sharing the same transportation and other infrastructure reduces the cost to each.

**(3) Income Generation.** Mission cost can be reduced through the generation of external income. By external income, we mean income not generated by demand within the colony itself, such as food, education, or utilities. Primary income generation for the Moon includes helium-3, lunar tourism, burial, co-branding, education and the arts, and infrastructure development.

### C. Reducing Operations Cost

The key issue in reducing long-term Earth-based operations is simple -- don't do it. By that we mean, don't set up an operations center on Earth that dictates all of the activities on the Moon or Mars. In any case, it is likely to generate more resentment than help on the part of the people that actually have to do the work.

## III. Extending Crew Stay

Bases, whether on the Moon or Mars, will undergo several phases [Eckart 1996]. Yet, when crew arrive, the earlier that they can extend their stay on the surface the sooner associated mission cost can be reduced.

This paper focuses upon the impact that extending crew stay would have on reducing mission cost. Crew rotations require recurring launches which place significant budgetary burdens on the programs. Every time that the crew at destination can extend their stay for an additional crew rotation this prevents the need to launch their replacements. Put another way, extending crew stay could results in a single crew launch instead of two resulting in cutting launch cost by roughly 50%. This reduction is perhaps comparable to more commonly thought of strategies for achieving cheaper space access. Yet it may not cost as much to develop the capacity to extend crew stay as it would to reduce mission cost by other means.

Figure 1 illustrates a comparison between two missions in which the first is conducted in the traditional manner in which ongoing launches results in crew rotations at Mars and the second mission involves extending crew stay. In addition to reducing launches from two to one, it can be seen that extending crew stay can also significantly increase surface time per launch. This is especially true for missions to Mars where in-space transit time constitutes a large portion of the overall mission duration.

It should be noted that extending crew stay can also significantly reduce the risk to crew since, for nearly the same amount of time at destination, the number of launch, entry, descent, and landing, ascent, and re-entry events would be cut in half. The fewer such risky events, the less likely that crew will be lost and the less risk for a lengthy and costly investigation and program delay.

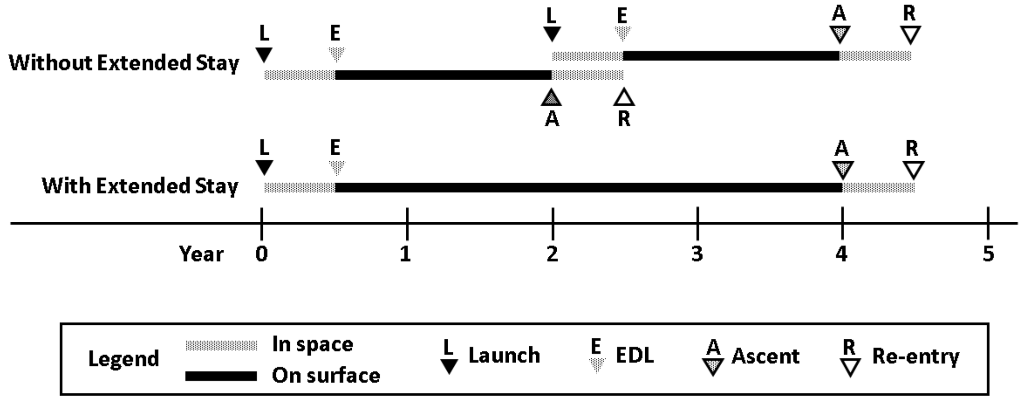


**Figure 1.** *Comparison of in-space and surface time and crew risk events between Mars missions employing extended stay or not.*

A final point to note is that the option of extending crew stay could serve as a safety net in the event that there was some failure causing the crew to be stranded at destination. By giving the crew the option to extend their stay, it would also buy the opportunity to mount a rescue operation and finding the crew still alive.

## IV. The Earth Return Option

It is here proposed, even with the initial set of crew, that they be given the option of returning as normal when the initial scheduled Earth return window opens using a fueled Earth return vehicle or, if specific preparations and strategies were employed, they could choose to extend their stay on the Moon or Mars for a minimum of an additional scheduled Earth return window. This would be neither a traditional 'flags-and-footprints' mission nor a one-way mission. Rather, the traditional return option would be available if they needed it but the goal would be to try to remain longer. An advantage of remaining at destination longer is that the crew would have more time for exploration and to build up the facilities and its capabilities. The program could also either save money by eliminating crew rotation launches or the crew launches could be continued at the regular pace, thereby accelerating the base's size and capability.

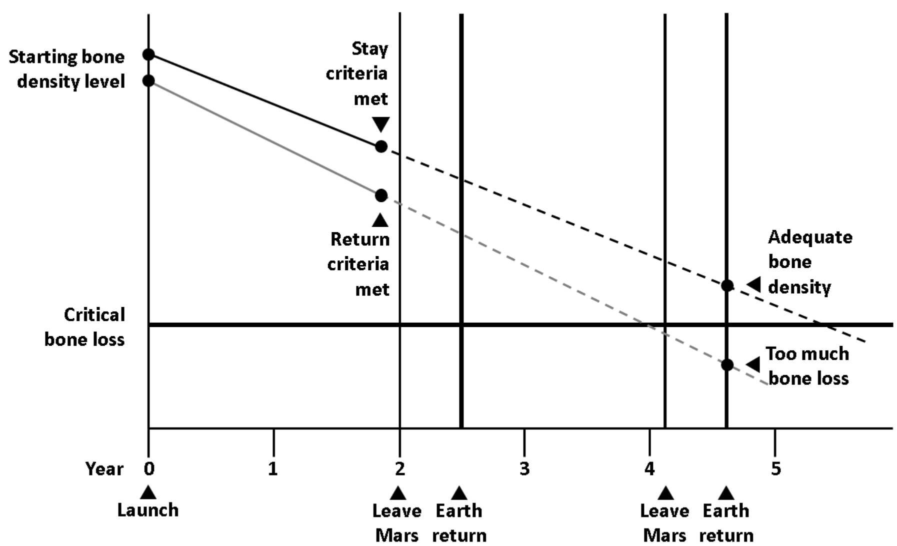


**Figure 2.** *Illustration of the Earth return criteria for bone minderal density.*

## V. Biomedical Criteria for Returning to Earth

Certain biomedical criteria can be established to determine if the crew is fit to be able to extend their stay until an additional Earth return window opens. It is beyond the scope of this paper to identify what those criteria might be.

But, as an example, the bone mineral density of the crew could be measured up until the first scheduled Earth return window opens (See Figure 2). If it is found that the rate of bone mineral density loss will place them below an acceptable level upon return to Earth then they would need to return at the first window. But if their projected bone mineral density loss upon return to Earth would not place them below a certain limit then they would have the option of extending their stay until the second window. Such an approach could be used for as many return windows as desired.

## VI. Sufficient Supplies & In-situ Resource Utilization

For crew to extend their stay, it would be essential that they have sufficient supplies to do so. Supplies could include those necessary for life support such as air, water, and food. But they would also need to include other consumables such as personal hygienic items and spare parts.

Supplies could and should be delivered before the crew arrives. It would be convenient to use lunar and Martian landers / ferries to deliver the supplies even while they were in the process of being human-rated through use. Additionally, while the crew is at the base, additional supplies could be sent thereby buying them even more time that they could stay.

The supplies should be in sufficient amount so that they would be able to remain until an additional scheduled Earth return window. But, if for some reason the resupply system were to fail, they should have already had enough supplies before arrival to be able to extend their stay. Similarly, the base could be supplied via ISRU [Criswell 1997] but if so, these systems would need to be reliable. It may be that a failure in some part of the system could result in reduced supply. This could either be a failure in the recycling, ISRU, or resupply systems.

## VII. Reliability of Life Support Systems

A second basic requirement for extending crew stay would be that the life support systems would need to be able to reliably function until the additional scheduled Earth return window opened. The life support equipment should be developed to a level of reliability to make this likely [Sargusingh 2014]. But in case of failure, the crew should have the spare parts and skills necessary to get the system working again. Redundant, back-up equipment could also increase the reliability of the system.

## VIII. Radiation Protection

For the discussion of radiation protection, let's choose a convenient 1,000 mSv for a nominal astronaut's career limit (47 year old male). NASA indicates that 20 g/cm$^2$ of water equivalent should be sufficient to mitigate solar particle events [Townsend 1992]. During a solar particle event, crew could position themselves within their water-bearing provisions to ride out the storm.

During transit to Mars, we propose that the crew be placed on a radiation budget in which, during their sedentary time (i.e. most of their time), their water-bearing provisions be positioned around their seat area but that they can, on occasion, exit this area into a larger, un-shielded habitat where they can exercise and otherwise ‘stretch their legs’. Figure 3 indicates that 50 g/cm$^2$ of water-equivalent shielding would reduce the GCR levels by approximately 62% [Simonsen 1997]. This comes to 0.68 mSv/day [Zeitlan 2013, Hassler 2014]. For a minimum-energy transit to and from Mars, total transit time would be about 461 days. This comes to 313 mSv or 31% of the career limit. For transit to and from the Moon, the radiation exposure would be negligible.

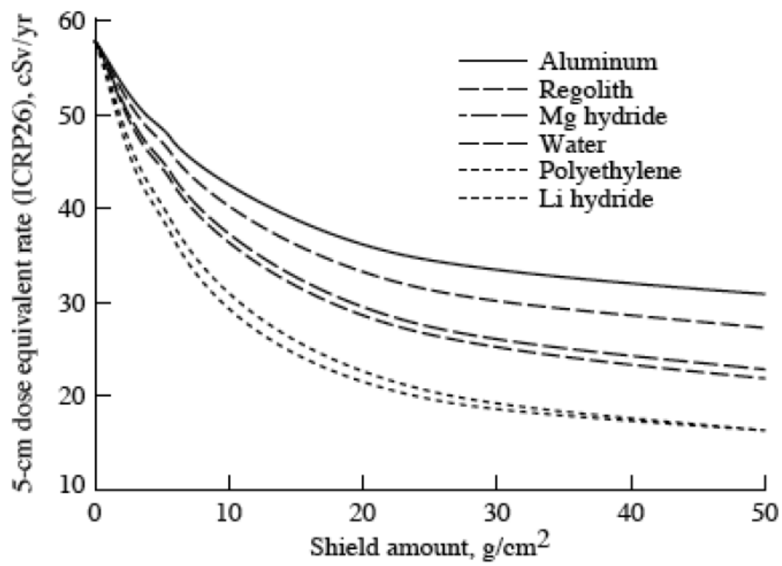


**Figure 3.** *GCR exposure versus depth of various materials [Simonsen et al. 1997]*

At destination, whether on the surface of the Moon or Mars, we propose that telerobots push regolith on top of habitats prior to crew arrival (See Figure 4). Figure 3 indicates that 50 g/cm$^2$ of regolith over the habitat would reduce GCR radiation by about 50%. With regolith having a density of 2.6 g/cm$^3$, this comes to a thickness of 19 cm. We consider this thickness of regolith covering to be well within the capability of teleoperated robots to push upon a flat habitat before inflating.

Taking into account these factors and the 50% reduction of radiation due to being on a planetary surface we estimate that the radiation levels within a shielded habitat would be approximately 0.45 mSv/day on the Moon and 0.41 mSv/day on Mars. This would bring the total radiation down to the realm of the International Space Station (0.41 mSv/day).

Together, we estimate that it would take 6.1 years before the 1,000 mSv career limit was met for a lunar mission and crew could remain on Mars for 4.6 years before their mission exceeded the 1,000 career limit. The crew could also maintain the telerobots which could continue to emplace more regolith on their habitat thereby buying the crew even more time before their career limits were met.

By these estimates it seems that, for either the Moon or Mars, the crew would not have to be concerned about their radiation exposure when considering whether they would have to return at the first scheduled Earth return window.

## IX. Artificial (Rotational) Gravity

For the long-term health of crew in permanent bases, artificial gravity may well be necessary to augment the hypogravity present. A number of approaches have been suggested [Young 1999]. In-space studies are necessary in order to fully test the health effects of artificial gravity. Unfortunately, to date, this issue has been insufficiently studied. We suggest that it is not absolutely essential to know how much artificial gravity is necessary before sending crew to the Moon for periods of a year or more. The crew could return with relatively short notice if biomedical measurements indicate.

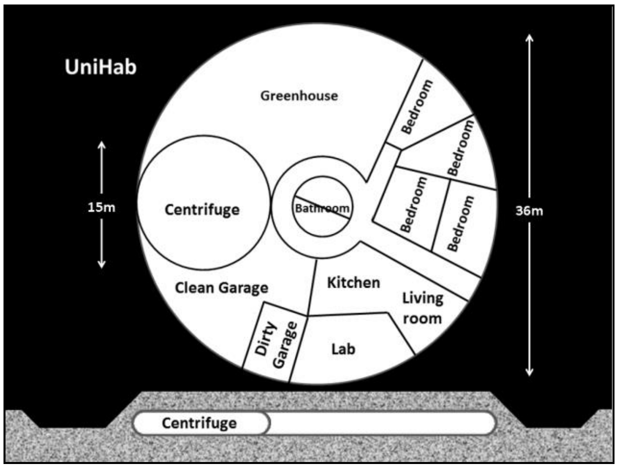


**Figure 4.** *Simple illustration of a large inflatable habitat covered by regolith for shielding and with an indoor centrifuge.*

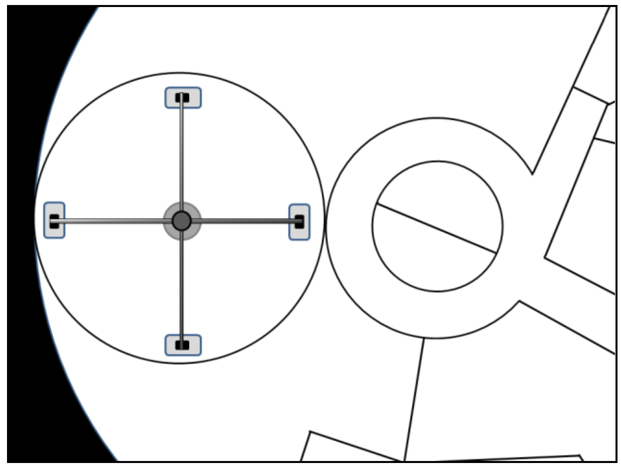

**Figure 5.** *Illustration of a low-mass, indoor centrifuge within a shielded habitat.*

However, the total duration of a minimum energy Mars mission is approximately 2.5 years which is beyond what we have experience with. We suggest that, for such a mission, tethering between the habitat and spent Earth departure stage and spinning up could provide a reasonable solution for microgravity during transit.

When on planetary surfaces, a centrifuge of approximately 15 meters in diameter within a shielded habitat could be used by the crew. An activity protocol should be considered which would approximate the distribution of hydrostatic pressure normally experienced by an active individual on Earth including the normal amount of time that individuals spend laying down, sitting, and standing. So we propose that the centrifuge provide 1 g so that the crew can get the normal 3-4 hours of full gravity while standing. When a crew member is laying down on Earth on the Moon or Mars, the difference in hydrostatic pressure between them would be relatively small due to the small fluid column height. But a large remainder of a typical individual's time is spent sitting in 1 g. It is not practical for crew on the Moon or Mars to sit in a confined centrifuge for this length of time. Consequently, an activity regimen involving increased standing in the habitat may help to partially mitigate some of the health impacts of living in reduced gravity.

However, the angular velocity needed to achieve a 1 g environment with this size of centrifuge is 11 rpm. Subjects turning their heads in this environment will experience a significant Coriolis effect but would not experience this if not turning their heads. So, the crew may be able to make use of their time in the centrifuge by conducting certain 'sedentary activities' that wouldn't require movement or head turning.

| | Activity | | Activity |
|---|---|---|---|
| 1 | Eating | 6 | Replying to e-mails |
| 2 | Lifting small weights | 7 | Sleeping |
| 3 | Listening to music | 8 | Surfing the Internet |
| 4 | Playing a video game | 9 | Video conferencing |
| 5 | Reading a book | 10 | Watching a movie |

**Table 2.** *Examples of sedentary activities able to be conducted in an 11 rpm centrifuge.*

To get an idea if this was possible, we visited a local theme park and arranged to ride a Gravitron at 11 rpm (See figure 6). We identified ten different sedentary activities (see Table 2) and attempted to conduct all of them. We found that, in fact, each of the activities was easily accomplished. We also attempted to sleep in this environment, but were unable to within the 15 minute time-frame that we were given. From our experience, we concluded that the off-Earth centrifuge would ideally need to be designed to be quiet, smooth, and with no visual reference of rotation. We also found that it was necessary to completely avoid movement of the head in order to avoid the very disconcerting Coriolis effect.

**Figure 6.** *Conducting sedentary activities within a 4-meter centrifuge at 11 rpm.*

## X. Social Factors Affecting Extended Stay

By employing various strategies to try and keep the crew on the Moon or Mars for as long as possible, it may be several years before the crew would have to return to Earth. Considering the length of stay, the social status of the crew could come into play for when the crew would need to return. There are strong advantages for the initial crew not having compelling social reasons for returning to Earth. If possible, they should have no young dependent children back on Earth. Neither should the crew be separated this long from a spouse back on Earth.

If the crew continues to live and work within a confined habitat for a period of years, the crew's martial status could become a significant factor. Having a mixed-gender crew of single individuals has worked fairly well for the ISS. But single crew may find the limited social opportunities of remaining for years at a permanent base to be difficult to manage until the population of the base grows significantly. Couples without children may find such an arrangement easier to handle. Yet such couples may aspire to eventually having children which would be problematic until animal studies indicate how children can be safely gestated and raised. Resolving these social challenges is beyond the scope of this paper. But we note that the social dimension needs to be addressed and that further studies are necessary.

## XI. Conclusions

There are a number of opportunities unique to crewed missions to reduce overall mission cost. We have focused upon five approaches which would allow for extending crew stay. These include: sufficient supplies, reliability of life support systems, radiation protection, rotational gravity, and ensuring that the initial crew's social status is compatible with extended stays. It appears that there may be readily available strategies to address these five factors. Extending crew stay would reduce crew rotation cost, reduce the risk of crew loss, and so set the stage for establishing a permanent off-Earth base.

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