

# Minimum Risk Deep Space Habitat and Life Support

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**A minimum risk space habitat design concept is developed for a Mars fly-by. The Inspiration Mars project first publicly suggested a Mars fly-by that would send two crew on a 500 day free return mission to Mars. Inspiration Mars proposed a high risk mission, designed to meet only the minimum human needs for survival, and intended to reduce mission cost to the minimum. The suggested minimum risk approach here is diametrically opposite, intended to reduce risk and provide maximum health and comfort, regardless of cost. The minimum risk approach includes two redundant habitats and two full life support provisions, artificial gravity, and many times the minimum recommended crew volume and water. Compared to the Inspiration Mars approach, the minimum risk habitat has thirty times the volume and twenty times the mass and cost. Probably the best approach lies between these two extremes and the cost-risk trade-offs should be investigated.**

## Nomenclature

|         |   |                                |
|---------|---|--------------------------------|
| CM      | = | Crewmember                     |
| EVA     | = | ExtraVehicular Activity        |
| ISS     | = | International Space Station    |
| LiOH    | = | Lithium hydroxide              |
| Pr LOC) | = | Probability of Loss of Crew    |
| Pr(LOM) | = | Probability of Loss of Mission |
| PRA     | = | Probabilistic Risk Analysis    |
| SSF     | = | Space Station Freedom          |
| TMI     | = | Trans Mars Injection           |

## I. Introduction

**T**HIS analysis investigates the habitat and life support requirements and system design for the minimum possible human risk on a deep space mission. Deep space missions will explore far beyond the Earth-moon system, to Mars or to an asteroid. Possible mission phases include launch, transit, orbit, surface exploration, return, and reentry. The mission assumed here is an Earth-Mars free return fly-by, a minimal mission without orbiting or surface exploration. Deep space missions have the new difficult challenge of supporting human life over a long mission using only the resources launched with the mission. All the required systems, replacements, spare parts, tools, materials, and operations and maintenance procedures must be planned and tested before the mission.

A risk is the possibility of loss or injury. Probabilistic Risk Analysis (PRA) is used in human space exploration, to estimate the Probability of Loss of Mission, Pr(LOM), and the Probability of Loss of Crew, Pr(LOC). These can be used to compare the risk of different missions, to minimize risk, and to allocate risk between mission elements and systems. Formal NASA risk analysis identifies the most important risks by estimating the likelihood of the risk in qualitative terms and then assessing its potential impact on the mission. Risk can be treated as a limited resource, like funding, to be allocated in the most efficient way. Or risk can be considered a reduction in the expected value or benefit of a mission. Advocates of better-faster-cheaper missions argue that more value is obtained by funding two equally important missions with say 80% probability of success than by putting all the funding into one mission to achieve a 90% probability of success. The problem is that one 90% success mission has only 10% chance of failure while two 80% success missions have a 36% chance of at least one failure. Accepting such high risk is unacceptable for science missions and unthinkable for crewed missions. There is a strong compulsion to reduce the risk of human space missions to the minimum.

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Human space travel creates unavoidable risks that may cause crew incapacity, injury, and death. Travel into deep space adds new risks and greatly increases the total mission risk. Assuming constant failure rates, a mission that is ten times longer has ten times the failure probability. Design decisions must be made that spend funding to decrease risk or conversely to incur risk to reduce cost. Each such design decision sets an implicit value on human life.

Setting a price on human life seems wrong, unethical. It cannot be done in space mission planning. To avoid this, the space shuttle designers adopted a deliberate willful blindness to risk. They did not do PRA or compute Pr(LOC). They accepted many unquantified risks to improve performance or cut cost. For example, the Challenger tragedy may have been avoided if the launch abort and crew escape systems had not been removed from the space shuttle to cut cost and increase payload. Amazingly, the shuttle risk of failure was officially misstated as 1 in 100,000 rather than the historically based 1 in 100.

Deliberately increasing human risk to improve performance and cut cost is difficult, but the sometimes preferred alternative of ignoring human risk can be disastrous. A different approach is needed to deal with the human health and safety risks associated with the habitat and life support. This analysis attempts to identify a habitat and life support design that has the minimum possible risk for the astronauts. Requirements are identified, design approaches are developed, and the implementation of the approaches discussed. The performance, mass, and cost results are compared with the maximum risk approach of Inspiration Mars.

## II. Minimum Risk Requirements and Design Decisions

The minimum risk requirements for the habitat and life support systems for Mars free return mission are developed using a top-down hierarchy of requirements and design decisions, following the principles of axiomatic design. The first axiom is to maintain the independence of the requirements, which is equivalent to maximally decoupling the hardware design. The second axiom is to reduce complexity as much as possible.<sup>1 2</sup>

The top level mission requirement and lower level habitat and life support requirements are developed. The overall mission requirement is: The Mars fly-by mission must send two crew members for 500 days on a free return expedition from Earth to Mars and bring them back as safely as possible. “As safely as possible” is a very challenging requirement, but what are its implications?

The level one habitat and life support requirement is:

R1 The Mars fly-by habitat and life support system must ensure the maximum comfort, health, and safety of the crew throughout the mission with minimum risk. “As safely as possible” requires minimizing the stress on the crew by maximizing comfort, health, and safety and by minimizing danger and risk.

The corresponding design decision to meet R1 is:

D1 The habitat and life support must use a closed pressurized spacecraft to provide secure Earth-like conditions. Maximizing crew comfort, health, and safety requires providing secure Earth-like conditions.

A partial parallel tree of requirements and design decisions is shown in Figure 1.

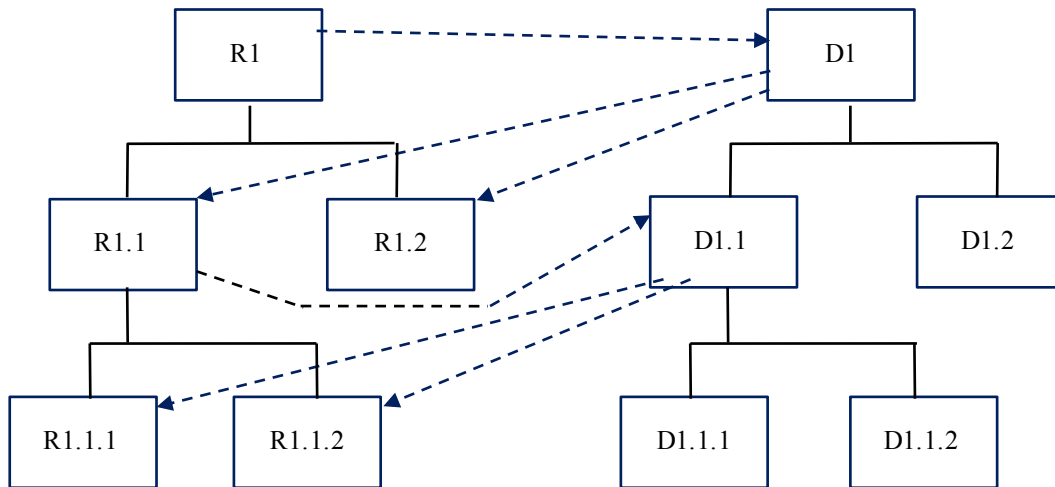


Figure 1. Decomposing and decoupling the requirements and design decisions.

The requirements and design decisions are decomposed and decoupled by zigzagging between successively lower levels. The second level requirements are divided between the habitat and life support. The level two requirements and design decisions are:

R1.1 The Mars fly-by habitat must provide artificial 1g gravitation, radiation protection, and human accommodations. Earth-like conditions include 1g gravitation and radiation protection. The corresponding design decision is:

D1.1 The habitat must rotate to provide gravitation and be shielded for radiation protection. The 1g environment will allow the equipment and human accommodations to be Earth- like designs, reducing risk and enhancing comfort.

R.1.2 The life support system must provide Earth-like atmosphere, food, water and waste treatment throughout the mission with minimum risk. The corresponding design decision is:

D.1.2 Atmosphere, food, and water must be stored and all waste must be treated for the entire mission.

The level three requirements flowing from D1.1 are:

R.1.1.1 The human habitat must rotate to provide 1 g gravitation. Access to all resources is required.

R.1.1.2 The human habitat must be shielded to minimize radiation risk.

R.1.1.3 The human habitat must include adequate space, facilities, and equipment for mission work, operations and maintenance, exercise, medical treatment, food storage, preparation and dining, and sleep.

The level three requirements derived from D1.2 are:

R.1.2.1 Oxygen, food, and water must be stored for the full mission.

R.1.2.2 Carbon dioxide removal must be provided for the full mission.

R.1.2.3 All waste including human metabolic products must be treated to minimize risk.

Instead of developing more detailed design decisions and requirements, the axiomatic design process will stop with these level three requirements. Ways to implement them are suggested at this very general level.

### III. Implementation of the Level Three Requirements

The suggested requirement for minimum risk habitat and life support for deep space has not previously been considered. This requirement directs attention to simple brute force habitat and life support designs that are well known and obvious, but are considered impractical because of their high launch mass. However, the most direct way to reduce risk from all sources, known and unknown, is to simplify the design. It is also important to increase robustness by providing excess delivery capability, buffers, and storage.

It has been assumed for decades that any Mars mission would use a habitat and regenerative life support system similar to that on the International Space Station (ISS).<sup>3</sup> ISS has zero gravity, little need for radiation shielding, Earth normal atmosphere except for excessive carbon dioxide, and recycles water and oxygen. Zero gravity is severely damaging to humans over a few months and high carbon dioxide levels impair performance. The ISS life support equipment is complex, unreliable, and difficult to repair, and even a refined higher reliability version would be very risky on a Mars mission. The actual working requirement for spacecraft habitats and life support seems to be to have minimum possible launch mass even at significant cost in crew comfort, health, and safety. This approach has increased ISS crew risk, but minimizing launch mass is now no longer necessary. Launch cost has been greatly reduced, by a factor of 10 or 20.<sup>4</sup> Life support using storage is now much less expensive than recycling systems, especially for smaller, briefer missions such as the Mars fly-by. Storage is also much simpler and lower risk than recycling.<sup>5</sup> The lower launch cost also decreases the cost of providing Earth gravity and radiation shielding. The minimum risk approach to habitat and life support design is definitely not the lowest mass or lowest budget approach, but given the extremely high cost of a risk that actually occurs, design for minimum risk may be the only justifiable approach. Certainly, the acceptance of any avoidable risk must be carefully considered.

#### A. R.1.1.1 The human habitat must rotate to provide 1 g gravitation. Access to all resources is required

Astronauts who spend many weeks or months in space in zero g suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system change.<sup>6</sup> Astronauts would be severely impaired during a 500 day Mars fly-by in zero g.

The usual designs for an artificial gravity spacecraft are a wheel, a cylinder, or two masses joined by a cable, which has less mass. A maximum rotation rate of 4 rpm is usually set to limit human susceptibility to the Coriolis effect, an apparent force felt in a rotating system. At 4 rpm, producing 1 g requires the diameter of a rotating wheel or cylinder to be 112 meters.

The suggested design is two identical habitats, one at each end of a cable. Each habitat will have half the total required living volume but the radiation shielding and life support required by two crew for the full mission.

Transfer between the two habitats will require airlocks, space suits, and support systems to move between the habitats. Multiple cables can improve stability and aid transfer. In studies of such systems, the cable's mass is usually neglected. It is typically 1% of the total system weight.<sup>7</sup>

This approach goes far to minimize risk. The crew can survive if one habitat becomes unusable or if the ability to transfer between the two habitats is lost.

**B. R1.1.2 The human habitat must be shielded to minimize radiation.**

Solar flares or particle events are the major radiation hazard in space. Solar flares are unpredictable but are more likely near the maximum of the 11 year sunspot cycle.<sup>8,9</sup> A safe haven for two astronauts during a solar flare is a 2 meter diameter aluminum sphere with 7.5 cm thick walls, weighing 20 g/cm<sup>2</sup> and a total of 2.5 metric tons (MT).<sup>9,10</sup>

Galactic cosmic rays have high energy but cause relatively little radiation damage compared to solar flares because of their low flux density compared to solar flares. On a 500 day Mars fly-by, an astronaut would accumulate 0.40 to 0.80 Sv of cosmic radiation, increasing the chance of a fatal cancer by 2 to 4% over a baseline of 22%. It is usually considered unnecessary to shield a spacecraft on a Mars mission against cosmic rays.<sup>8</sup>

**C. R.1.1.3 The human habitat must include adequate space, facilities and equipment for mission work, operations and maintenance, exercise, medical treatment, food storage, preparation and dining, and sleep.**

NASA recommends human spacecraft have a minimum habitable volume of 25 cubic meters per person.<sup>9</sup> This far too little for maximum comfort and minimum risk. The ISS pressurized volume is 915.6 cubic meters. For the maximum six astronauts, this is 152.6 cubic meters per crewmember. Using 150 cubic meters, the minimum risk habitat will have 300 cubic meters for two crew. The ceiling height will be 3 meters, roughly 10 feet, and the floor area 100 square meters, 10 by 10 meters. The mass of the ISS is 419,725 kg, 458 kg per cubic meter. At the ISS density, the mass of the habitat will be 137,524 kg, about one-third of ISS. The habitat will be split into two equally sized habitats, rotating at each end of a cable.

This large area and the presence of Earth normal gravity will allow the use of familiar terrestrial equipment and human accommodations. Robustness through excess capability and high reliability and maintainability are required and must be demonstrated for durations longer than the 500 day fly-by duration. Very high fidelity mission simulations must be performed and include both preprogrammed and spontaneous unexpected internal failure modes and external emergencies. The next two requirements require storage and are considered together.

**D. R.1.2.1 Oxygen, food, and water must be stored for the full mission, and, R.1.2.2 Carbon dioxide removal must be provided for the full mission.**

Providing oxygen and water in tanks, packaged food, and lithium hydroxide (LiOH) canisters for carbon dioxide is the usual life support approach for short missions. The ISS will operate more than 20 years, so the life support system recycles oxygen and water, and removes carbon dioxide using a regenerable system. Table 1 provides the masses of the stored life support materials and their container for the Mars fly-by.

Table 1. Masses of oxygen, food, water, LiOH, and their containers per crewmember day (CM-d).

| Material             | Use rate, kg/CM-d | Packaging ratio | Total mass need, kg/CM-d |
|----------------------|-------------------|-----------------|--------------------------|
| Oxygen               | 0.84              | 1.36            | 1.14                     |
| Hydrated food        | 1.77              | 1.36            | 2.41                     |
| Food prep water      | 0.76              |                 |                          |
| Drink                | 1.62              |                 |                          |
| Hand/face wash water | 4.09              |                 |                          |
| Shower water         | 2.73              |                 |                          |
| Flush water          | 0.49              |                 |                          |
| Clothes wash water   | 12.5              |                 |                          |
| Dish wash water      | 5.45              |                 |                          |
| Total water          | 27.64             | 1.21            | 33.33                    |
| Carbon dioxide out   | 1.00              |                 |                          |
| LiOH needed          | 1.30              | 1.35            | 1.75                     |
| Total, kg/CM-d       |                   |                 | 38.63                    |
| Mission total, kg    |                   |                 | 38,628                   |

The oxygen, food, and LiOH requirements are for an average crewmember and vary with gender, weight, and activity. These consumed mass requirements were developed originally for Space Station Freedom (SSF).<sup>10</sup> The water includes requirements for showers, clothes washing, and dish washing totaling 20.68 kg/CM-d, but these were removed for ISS. The remaining 6.96 kg/CM-d of water is roughly that required on ISS, but the full SSF 27.65 kg/CM-d water requirement provides a more comfortable Earth-like environment. If ISS rather than SSF water requirements are chosen, 75 percent of the water mass would not be required.

A space qualified oxygen tank weighs 12.7 kg and contains 35.4 kg of oxygen, a 1.36 total to content packaging ratio.<sup>11</sup> The space shuttle food mass is 3.8 pounds CM/day including 1 pound of packaging, also a 1.36 total to content packaging ratio.<sup>12</sup> A space station water tank weighs 21.2 kg and holds 103 kg of water, a 1.21 total to content packaging ratio.<sup>13</sup>

Carbon dioxide is removed using lithium hydroxide (LiOH) in canisters. The filled shuttle LiOH canister weighs 7 kg and is rated at 4 crewmember-days, so the required resupply mass of LiOH plus canister is 1.75 kg/CM-d.<sup>14</sup> The LiOH and canister masses are estimates. About 1.1 kg of LiOH is chemically required to remove the 1.0 kg of carbon dioxide per crewmember per day.<sup>15</sup> The ISS LiOH canister provides about 1.5 kg/CM-d of LiOH.<sup>16</sup> Estimating 1.3 kg/CM-d of LiOH, the total to content packaging ratio is 1.35.

The current high levels of carbon dioxide on ISS can cause headaches and behavioral changes. Using the ISS regenerative carbon dioxide removal equipment, it is not feasible to achieve earth-normal values of carbon dioxide.<sup>17</sup> However, LiOH can achieve very low levels before carbon dioxide breakthrough and replacement of the canister.<sup>18</sup>

The daily total mass needed is 38.63 kg/CM-d. The total mission mass for oxygen, food, water, LiOH, and their containers for 2 crew over 500 days, 1,000 CM-d, is 36,630 kg. Since these containers are small, filling only a few days or weeks need, there will be very many of them. Since they are highly reliable, only a small percentage of spares will be needed.<sup>19</sup> Since the bulk of the material is water with a specific gravity of one, the 38,628 kg will fill approximately 38,628 thousand cubic centimeters or 38.6 cubic meters, much less than the 600 cubic meters in the habitat. Each of the two rotating habitats will contain the entire life support mass for two crew over the entire mission.

#### **E. R.1.2.3 All waste including human metabolic products must be treated to minimize risk.**

Human metabolism produces carbon dioxide, perspired and transpired water, urine and feces. Carbon dioxide can be removed by LiOH and remains in the used canisters. Humidity in the atmosphere must be removed, usually by a condensing heat exchanger that produces waste water. Other waste water includes used wash and shower water and urine and flush water. Feces are typically collected and stored in sealed containers. Other waste includes food packaging and drink containers.

The basic approaches are to store the wastes safely or to vent liquids and jettison solids. On a free return fly-by, no thrust is needed to return to Earth, so reducing the return mass saves nothing. Jettisoning waste through an airlock can potentially foul the spacecraft, but the habitat's 1 g rotation would quickly send it away. The operation and even the presence of liquid vents and airlocks increases risk. The minimum risk design is on-board storage of all wastes with suitable treatment and containment.

Much of the waste water, humidity condensate, and used shower and wash water could be recycled for use as wash or flush water, substantially reducing water storage and launch mass. However, recycling would have lower reliability and higher cost.<sup>19</sup>

### **IV. Comparison with Other Mars Fly-by Missions**

The first widely known proposal for a manned Mars free-return mission, Inspiration Mars, was made by Dennis Tito and colleagues in 2013 for a 2018 mission. With support from Paragon Space Development Corporation and NASA AMES Research Center, he published a detailed feasibility analysis of their proposed mission.<sup>20</sup> In 2014, the Viamana Design Team in India developed a Mars fly-by mission architecture.<sup>21</sup> Both are 2 crew, 500 day fly-bys. These suggested architectures are similar to each other but are notably different from the minimum risk, unconstrained cost approach taken here. Table 2 compares the three approaches.

Table 2. Comparison of the minimum risk, Inspiration Mars, and Viamana Mars fly-by architectures.

| Element                                             | Cost, \$/kg         | Minimum risk               | Inspiration Mars                | Viamana                    |
|-----------------------------------------------------|---------------------|----------------------------|---------------------------------|----------------------------|
| Risk                                                |                     | Minimum risk               | High risk                       | Some risk reduction        |
| Approach                                            |                     | Maximum health and comfort | Basic human survival needs only | Increased water, not space |
| EVA                                                 |                     | Yes                        | No                              | Yes                        |
| Number of habitats                                  |                     | 2                          | 1                               | 1                          |
| Privacy                                             |                     | As desired                 | None                            | None                       |
| Habitat gravity, g                                  |                     | 1                          | 0                               | 0                          |
| Atmosphere                                          |                     | Earth normal               | Earth normal                    | Earth normal               |
| Radiation protection                                |                     | Metal shielding            | Water shielding                 | Magnetic field             |
| Volume, m <sup>3</sup> /CM                          |                     | 150                        | 5.1                             | 4.45                       |
| Total habitat volume, m <sup>3</sup>                |                     | 300                        | 10.2                            | 8.9                        |
| Total habitat mass, kg                              |                     | 140,024                    | 4,672                           | 10,000                     |
| <b>Habitat cost, \$k</b>                            | <b>78.6</b>         | <b>11,005,886</b>          | <b>367,188</b>                  |                            |
| Life support approach                               |                     | Storage                    | ISS-like recycling              | ISS-like recycling         |
| Water, kg/CM-day                                    |                     | 27.64                      | 1.20                            | 3.91                       |
| Life support redundancy                             |                     | 2                          | None - single thread            | 2                          |
| Life support recycling mass, kg                     |                     | 0                          | 2,432                           | 8,000                      |
| Life support stored material and container mass, kg |                     | 77,256                     | 3,131                           | 9,700                      |
| <b>Life support recycling cost, \$k</b>             | <b>78.6</b>         | <b>0</b>                   | <b>191,155</b>                  |                            |
| <b>Life support stored material cost, \$k</b>       | <b>20.1</b>         | <b>1,451,705</b>           | <b>62,962</b>                   |                            |
| Total mass, kg                                      |                     | 217,282                    | 10,235                          | 27,700                     |
| <b>Total mass cost</b>                              |                     | <b>12,457,592</b>          | <b>621,305</b>                  | <b>820,000</b>             |
| <b>Operations cost</b>                              | <b>10% per year</b> | <b>1,877,171</b>           | <b>93,621</b>                   | <b>250,000</b>             |
| Launcher                                            |                     | Falcon Heavy               | Falcon Heavy                    | Russian Angara             |
| <b>Launch cost, \$k</b>                             | <b>10.7</b>         | <b>2,324,917</b>           | <b>109,510</b>                  | <b>1,600,000</b>           |
| <b>Total cost, \$k</b>                              |                     | <b>16,659,680</b>          | <b>824,437</b>                  | <b>2,670,000</b>           |

Instead of minimum risk, Inspiration Mars assumes very high risk to reduce cost. “The journey is treated as a high-risk mission, which drives towards reliable—but minimalist—accommodations and provisions.” The life support “was assumed to meet only basic human needs.”<sup>20</sup> The Viamana design follows Inspiration Mars in some respects, but reduces risk by using full redundant life support, as does the minimum risk approach. ISS-like recycling life support cannot be considered reliable. Storage is very much more reliable.<sup>19</sup>

The minimum risk approach provides maximum health and comfort, Inspiration Mars meets only basic survival needs, and the Viamana approach provides three times more water but 13 % less space. The minimum risk spacecraft has two identical habitats which provide privacy. The two minimum risk habitats are in a rotating structure that provides 1g. This requires ExtraVehicular Activity (EVA) to travel between them. Inspiration Mars and Viamana have 0 g, Viamana also plans EVA for extended mission transfers. All designs provide Earth normal atmosphere and radiation shielding, but Inspiration Mars and Viamana use mass-saving shielding approaches, The minimum risk design volume is 300 m<sup>3</sup> six times the recommended 25 m<sup>3</sup>/CM, while the Inspiration Mars and Viamana approach provide less than one-fifth the recommendation, a volume reduction of 30 times from the minimum risk volume.

The Viamana habitat mass, but not its specific cost, are provided in the mission description. The minimum risk and Inspiration Mars habitat mass and cost are estimated using ISS data. The ISS pressurized volume is 915.6 cubic meters. The mass of the ISS is 419,725 kg, 458 kg per cubic meter. The minimum risk habitat mass of 140,024 kg includes 137,524 kg for the habitat plus 2,500kg for the radiation shield. The ISS cost has been estimated at \$150 billion, including \$50 billion for shuttle launch. The design and operations cost is \$100 billion. Space operations

cost is about 10 percent of the design cost per year over 20 years of operations, or a total of 200% of the design cost. The ISS cost breakdown is then \$33 billion for the ISS, \$50 billion for launch, and \$66 billion for operations. The mass of the ISS is 419,725 kg, so its mass cost is \$33 billion/419,725 kg = 78.6 \$/kg.

The minimum risk approach uses full storage life support, including oxygen, water, and LiOH. "Life support systems that depend on storage of all consumables are typically the simplest and most reliable,"<sup>20</sup> Inspiration Mars and Viamana use similar ISS-like recycling life support, but Viamana provides about 3 times the water and requires similar increases in recycling and storage masses. Both Inspiration Mars and Viamana require more mass for life support than for the habitat. The minimum risk storage life support approach requires 30 times the habitat mass of Inspiration Mars.

The Viamana life support costs are not specifically identified. The recycling life support cost for the minimum risk and Inspiration Mars approaches is estimated using the same ISS-derived mass cost used for habitat mass, 78.6 \$/kg. The resupply life support cost for all architectures was estimated from previous work.<sup>19</sup> The cost of resupply is not for the oxygen, water, and LiOH, but for their tanks and canisters. Flight qualified containers were considered and detailed mass and cost calculations were made for oxygen, water, and LiOH. These calculations produce an overall average cost of 20.1 \$/kg for the total supply and container mass. Since the packaging mass is roughly 20% of the contained mass, the mass cost of the containers themselves is roughly 120 \$/kg, higher than for the habitat.

For the minimum risk and Inspiration Mars approaches, the total mass and the total cost to provide the mass can be simply summed up. Operations costs are typically about 10% of the hardware development cost per year. The cost of Falcon Heavy launch to Trans Mars Direction (TMI) has been estimated as 10.7 \$/kg.<sup>20</sup> Summing up total mass (habitat and life support) cost, operations cost, and launch cost gives the total cost. The minimum risk storage life support approach requires 20 times the cost of Inspiration Mars.

The costs for the Viamana approach are stated in the project report. These Viamana costs would be different if the same assumptions were used as for minimum risk and Inspiration Mars. This is shown in Table 3.

Table 3. Viamana costs as stated and revised using the methods for the minimum risk and Inspiration Mars.

| Element                                             | Cost, \$/kg         | Viamana report   | Viamana revised  |
|-----------------------------------------------------|---------------------|------------------|------------------|
| Total habitat mass with shielding, kg               |                     | 10,000           | 10,000           |
| <b>Habitat cost, \$k</b>                            | <b>78.6</b>         |                  | <b>786,000</b>   |
| Life support recycling mass, kg                     |                     | 8,000            | 8,000            |
| Life support stored material and container mass, kg |                     | 9,700            | 9,700            |
| <b>Life support recycling cost, \$k</b>             | <b>78.6</b>         |                  | <b>628,800</b>   |
| <b>Life support stored material cost, \$k</b>       | <b>20.1</b>         |                  | <b>195,060</b>   |
| Total mass, kg                                      |                     | 27,700           | 27,700           |
| <b>Total mass cost</b>                              |                     | <b>820,000</b>   | <b>1,609,860</b> |
| <b>Operations cost</b>                              | <b>10% per year</b> | <b>250,000</b>   | <b>220,529</b>   |
| Launcher                                            |                     | Russian Angara   | Falcon Heavy     |
| <b>Launch cost, \$k</b>                             | <b>10.7</b>         | <b>1,600,000</b> | <b>296,390</b>   |
| <b>Total cost, \$k</b>                              |                     | <b>2,670,000</b> | <b>2,126,779</b> |

For the Viamana design, using the ISS mass cost per kilogram doubles the total mass cost. Even doubling the mass cost basis of operations cost leaves the total operations cost about the same. The most notable difference is that the use of the Falcon Heavy reduces the launch cost by more than 90%.

Compared to Inspiration Mars, the Viamana approach maintains the very small volume, doubles the habitat mass, roughly triples the life support mass, and roughly doubles the total cost. The Viamana approach is somewhat similar to the Inspiration Mars approach, but it reduces risk and increases cost by increasing life support water and by providing dual redundant life support. The next steps to gradually improve crew conditions would be to increase crew volume and to provide more than survival level water safely stored. A major step would be to provide artificial gravity at 1 g.

## V. Conclusion

A Mars fly-by spacecraft providing minimum risk and maximum health and comfort would cost twenty times as much as the high risk Inspiration Mars spacecraft that provides only the minimum basic survival human needs. These are the two extreme risk approaches. Some intermediate risk design seems called for. It would be beneficial to explore not just other discrete point designs, but instead find the design path that incrementally provides the cost-

effective risk reduction. Some improvements can be made incrementally, such as more water, crew volume or redundancy. These would have diminishing returns and require trade-offs. Other improvements such as providing a refuge habitat or artificial gravity would require a discrete step design change. Often mixed strategies are best, such as providing the needed survival water in storage and increase comfort water by less reliable lower mass recycling. Understanding the deep space habitat cost-risk trade-off will require explicitly quantifying cost and risk.

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