Artificial Gravity in Mars Orbit for Crew Acclimation

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Abstract— **NASA's current baseline plan for a crewed Mars mission anticipates a transit time of up to three hundred days in microgravity and 3-14 days on the Martian surface for gravity acclimation before the crew can safely perform their first Extra-Vehicular Activity (EVA). While there are multiple options for how initial surface operations will be performed, all current designs involve acclimation on the surface, and the impacts on the mission schedule, required supplies, and crew lander systems are significant.**

This paper proposes an alternative option utilizing artificial gravity, which offers benefits in terms of mission scope, mass savings, crew health, and long-term strategic vision. By moving the acclimation requirement to the orbiting habitat's existing systems, rather than adding redundant systems to the lander, the Mars Descent Vehicle (MDV) can be a much smaller, simpler, and lighter design. Rather than the lander being designed to support crew for days, it would be mere hours.

While ambitious, the concept of pre-acclimation in orbit can be not only safe and feasible, but done with fairly minimal changes to the planned architecture and overall mass requirements. The data used draws on decades of established research and demonstrates how this capability can be not only used for pre-acclimation, but also to support crew during early orbital-only missions, surface abort contingency scenarios, return-to-orbit abort scenarios, and as an early proof of capability into larger and more ambitious artificial gravity designs needed for extended exploration missions in the future.

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1. INTRODUCTION

While many relegate the concept of artificial gravity to the world of science fiction, it is important to remember that for decades it was assumed to be as integral to long-term spaceflight as the rocket itself, but it was ultimately sidelined due to the increased focus on microgravity research after the Apollo moon landings. As early as 1895, scientists proposed using centrifugal force to simulate gravity in space [1], as they recognized the benefits of maintaining a similar environment during spaceflight to that in which humans have evolved. Additionally, it resolves many of our most nagging issues with spaceflight which are direct results of microgravity.

This paper draws from more than two decades' worth of research into artificial gravity and bio-acclimation to rotating frames of reference, and compiles some useful pieces to show how the use of artificial gravity could be added to the NASA Mars Study Capability's (MSC) Concept of Operations (Con-Ops) and the additional safety and crew biological benefits that would derive from its availability. This design has been generated with a focus on mass-neutrality within the existing Con-Ops, demonstrating mass offsets and savings available through its implementation.

2. HISTORICAL BACKGROUND

In March 1952, *Collier's* Magazine released an edition of their monthly magazine that would go on to greatly alter the path of the western world and influence the course of geopolitics for the next two decades. Five years before the launch of Sputnik and 6 years before NASA was founded, its

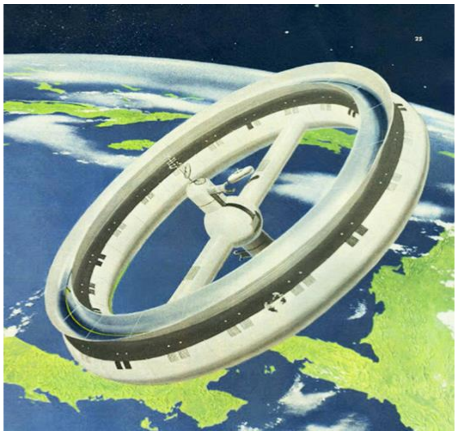

Figure 1. Space station concept design, Colliers Magazine, March 1952

articles laid out a plan for space travel and introduced the American public to a wide array of new concepts – staged launch vehicles, in-space assembly of payloads, in-orbit observatories, satellites, EVA, Micro-Meteoroid Orbital Debris (MMOD), and ultimately the hardware necessary to land on the moon [2]. The massive response to this and the six subsequent *Collier's* specials over the next two years helped convince most skeptics that the frontier of space could be tamed.

In reality, this plan was nothing more than an ambitious goal shared by a few. The U.S. manned space program consisted of only a small team of American and German scientists launching experiments in captured V-2 rockets from White Sands Test Range. Yet these small bands of visionaries had been pondering what life would be like for early space pioneers for decades.

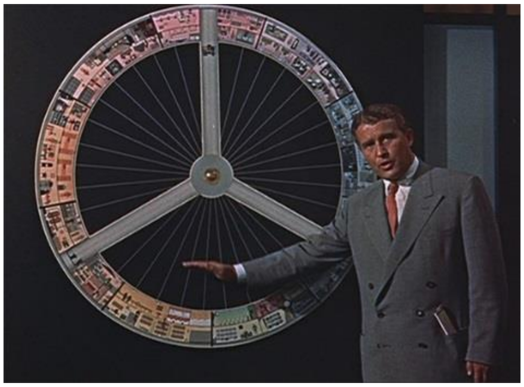

Figure 2. Von Braun demonstrating a space station design on "Man in Space," 1955

The concepts shown in Colliers were pitched to the American Ballistic Missile Agency and U.S. Air Force as an orbital Earth-viewing station and potential weapons platform [3]. This station would have maintained a permanent crew of eighty people in two decks and would have taken a massive effort to create, costing the 2018 equivalent of $38 billion, twice that of the Manhattan Project [2]. For a time, this concept for an Earth-viewing station was a very real possibility, and it had its supporters in Washington as past experience had shown that the "high ground" was strategically critical to winning any future military conflict.

In 1955, with public interest piqued and with the concepts of space travel permeating into every aspect of popular culture, Von Braun and Walt Disney agreed to collaborate for the new TV series "Walt Disney's Wonderful World of Color." "Man in Space", an Oscar-nominated documentary in the series, featured Von Braun as he demonstrated how humans could be soon working, living, and exploring space. The primary focus of space station design was crew comfort and long-term habitability, and the logical choice was a rotating torus.

Three years later NASA was founded, and these visionaries joined the civilian agency, turning the proposed weapons platform into an orbital observation post with a wide array of telescopes and Earth-viewing weather facilities onboard. In 1959, a NASA committee recommended a large rotating space station as a logical follow-on to the Mercury program and staging area for Earth-Orbit-Rendezvous (EOR)-based lunar missions [4]. This derivative of Von Braun's design would require a fleet of shuttles, rockets, and specialized assembly spacecraft over the next decade.

In fact, this concept may have eventually become a reality, at least in part, if it had not been for the simmering space race between the USA and the USSR, and America's desperate need to keep up with the Soviets' early successes. While the U.S. had launched a dummy satellite with an inert upper stage in 1956 as a precursor for Earth-orbiting satellites, the surprise launch of Sputnik in 1957 coupled with the very public failure of the U.S. Navy's Vanguard launch in response, left America on the back foot early in this race. NASA would spend the majority of the 1960s playing catch-up as the Soviets tacked together an impressively long list of space "firsts."

In May 1961, three weeks after America's first suborbital flight, President Kennedy gave his new agency a very ambitious goal – establish America as a space power and land astronauts on the surface of the moon by 1970. At this point, America had fifteen minutes of manned spaceflight, and the level of audacity to make this challenge verged on either insanity or hubris. Nonetheless, after speaking to NASA leadership—many of whom had been authors of the *Collier's* articles a decade earlier—Kennedy was convinced it was possible, but at a cost. That cost was a large space station.

In reality, the large toroidal design had many flaws and would likely have never been launched by NASA. Estimates suggested it would require at least a decade to build [5], and the emergence of modern computing and improving communications meant that orbiting telescopes would soon not need crew to operate them. With funds needed for Gemini and Apollo, a tight timeframe, and a diminishing raison d'etre, the large rotating spacecraft would ultimately remain just a concept.

The push for a smaller space station continued however: a modular design that could be launched in a few flights as a testbed for further exploration. From 1961-1962, the proposal for landing on the moon still included EOR, but as the engineers dug into the details, it became increasingly clear that this was not an option within the limited number of launches and with the complexity required. NASA had to adjust their plan to a Lunar Orbit Rendezvous (LOR)-type mission and postpone any dedicated space station until after the moon landings. The national focus was on the moon, and once it was clear that a permanent space station in Earth orbit wasn't necessary to reach that goal, it was shelved.

Even then, the concept designs did not completely end, they were merely pared down once more. Between 1962 and 1964, plans were drawn up for a small space station that would fly co-manifested with a Gemini capsule and could be used for extended missions. When the Gemini flights ended and Apollo began, they were again modified and proposed all the way up through 1970 where it finally lost out to the Skylab project.

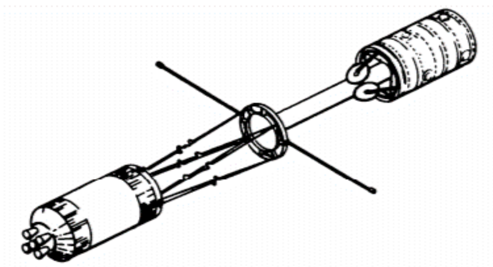

Figure 3. MORL design utilizing a habitat and spent SII stage as a countermass, spinning about a central winch ring in an artificial gravity configuration, MSFC 1970

These flights were similar to the Salyut space stations that the Soviets were using and would have been deployable in either microgravity or partial artificial gravity, depending on the research requirements. This space station design was known as the Manned Orbiting Research Laboratory (MORL), and it was the brainchild of the Douglas Aircraft Corporation [6]. This paper draws inspiration from each of these sources and borrows significantly from the basic proposed design of the MORL itself for its capabilities.

3. MARS STUDY CAPABILITY CON-OPS

In order to better understand how this architecture will be utilized, it is necessary to establish the MSC Con-Ops and the buildup schedule needed to meet those goals. Much like the incremental tests and processes that were used during the Mercury, Gemini, and Apollo era, the Mars Study Capability Team seeks to take manageable steps forward to ensure the readiness of crew and hardware at each milestone. The following sections will outline these briefly.

Lunar Gateway

The Gateway is a small space station planned for the near-term which will be placed in an elliptical orbit around the moon. Preliminary designs are comprised of a power-propulsion bus, a node for docking to visiting vehicles and other modules, and at least one permanent habitation module [7]. Among other roles, the Gateway will be used as a staging area for initial buildup, outfitting, post-mission renovation, and upkeep of the Deep Space Transport (DST). Its life support systems, airlock, and robotic arm will be available to ensure the DST is fully prepared before each Mars mission. This DST will be the vehicle responsible for safely transporting the crews to and from Mars, and must keep them safe for the full duration of the mission, up to 1200 days. As such, it is expected to be significantly larger than most previously flown monolithic modules.

DST Checkout & Shakedown Mission

It will be necessary to outfit the DST while it is docked to the Gateway because its fully-outfitted mass will likely exceed the capabilities of launch vehicles available [8]. This will be done by using co-manifested logistics and Orion flights, whose crews will complete the initial outfitting and systems check. The outfitting crew will then return to Earth and a new Orion capsule will be launched to the Gateway. This new crew will board the DST, separate from the Gateway, and enter a nearby orbit where it will remain completely autonomous for a year-long test run in the Earth/moon vicinity. This will be where all systems capabilities are demonstrated and any potential issues worked out, while maintaining the option of retreating to the Orion and returning to Earth in case of catastrophic emergency.

Orbital Mission

Once the DST has passed the shakedown mission, it will return to the Gateway for outfitting prior to the first Mars mission. After a Trans-Mars Injection (TMI) burn and transit, the DST will insert into Mars orbit and the crew will remain there until the next optimum return window. This will be approximately 500 days depending on transit velocity and orbital alignment. This mission will test the long-distance communications, rendezvous, and docking of return stages and landers, in addition to fully testing the long-term isolation and microgravity requirements for future crews.

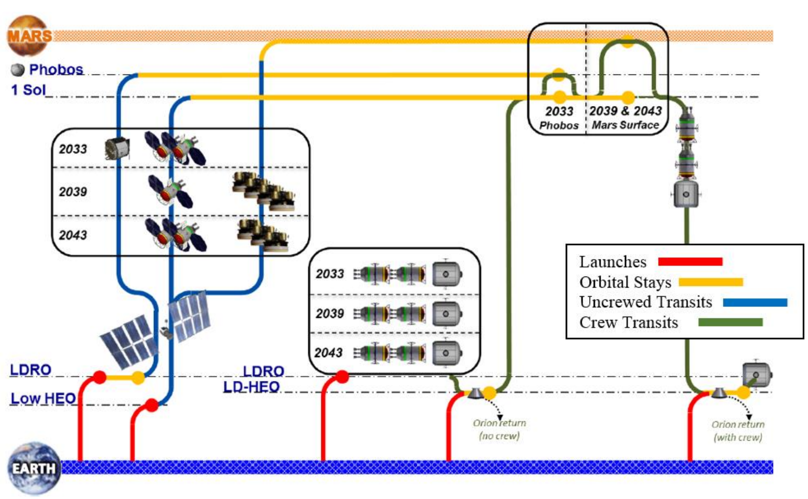

Figure 4. Depiction of Mars buildup capabilty from cis-lunar space for a crew surface mission using chemical propusion

The orbital mission would be an ideal opportunity for the application of artificial gravity. If applied for the same period of time as the future crews are expected to stay on the Martian surface, crews could experience much more realistic simulation of musculoskeletal effects from partial gravity on Mars surface while in a more controlled environment.

Surface Missions

The cadence for Mars missions is driven by three factors:
1. the duration of each mission, 950-1100 days average
2. the time required for re-outfitting after each mission
3. The ~26-month Mars transfer opportunity window.

Because there are plans for only a single transit habitat in the near term, and each round-trip mission will be longer than the ~26 month transfer window, or approximately every 52 months.

The surface missions will be very similar to previous missions insomuch as they will use TMI stage to push the DST toward Mars and the Mars Orbital Insertion (MOI) stage to enter Martian orbit once it arrives. It will then dock to the full return stages as well as the MDV, which the crew will use to leave the DST and descend to the surface. At the end of the surface mission, crews will return to the orbiting DST in the pre-supplied ascent vehicle [9].

4. Fundamental Calculations for Generating Artificial Gravity

The following equations serve as a reference for calculations shown throughout the paper. While the dynamics of a rotating system can become rather complex when one introduces factors like vibrational loading and precession, there are a few basic equations that can help decide whether a design meets general criteria requirements.

Artificial gravity is a measurement of the centrifugal acceleration vector α and is a function of the rotational velocity and the radius:

$$\alpha = -\omega^2 r \qquad (1)$$

Where the rotational velocity ω is constant at all points on the object in rotation, and in this paper measured in revolutions per minute (RPM). The gravitational equivalent (often called “g” level) is given as a ratio of the centrifugal acceleration and the gravitational constant at Earth sea level:

$$g = \alpha / g_E \qquad (2)$$

The tangential rim velocity v at any point in the system is a function of rotational velocity and the distance from the center of rotation:

$$v = \omega r \qquad (3)$$

For ”barbell”-type spacecraft designs like the one proposed, the segments can be simplified to point masses to estimate the system’s center of rotation and find the gravitational gradients within the habitat. The force is calculated via:

$$F = mr\omega^2 \qquad (4)$$

The force balance for a simplified three-part system is then:

$$(mr\omega^2)_{habitat} + (mr\omega^2)_{cable} + (mr\omega^2)_{stage} = 0$$

Where the angular rotation (ω) for each is the same. This leaves the relationship purely dependent upon the mass and radii once the system is stable.

Meanwhile, one of the biologic limitations is excessive Coriolis force, which is calculated using:

$$F_c = -2m(\omega \times v)$$

This phenomena occurs when a rotating reference frame (in this case a spacecraft) interacts with a relative linear motion (v), such as a person walking in a direction non-parallel to the direction of rotation. That person’s motion will trace out an arc, rather than a straight line, due to this additional force. This Coriolis Effect can be a hurdle to crew comfort, especially at high or varying rates of rotation. Understanding this relationship will help clarify why the overall angular momentum is such a significant design driver.

5. Design Limitations

Rotation Rate—NASA spent nearly two decades researching the effects of both weightlessness and artificial gravity on the human body, both through direct research and industry partnerships. Most of this research is publically available online, and some aspects of applicable research continue on through military Research and Development and at places like the Ashton Graybiel Spatial Orientation Laboratory and the U.S. Naval Aerospace Medical Institute.

Through countless papers, presentations, articles, and tests, a massive trove of data has been compiled, outlining conditions for adaptation as well as establishing some suggested limitations for crew activities. This paper provides a simple summary of the most pertinent constraints when designing for artificial gravity, and should not be considered a comprehensive list, merely engineering guidelines for human comfort.

Upper limits for rotation rate vary depending on crew, activities involved, and whether or not the crew will receive an acclimation period. For an Earth-similar system, a rotation rate of 2 RPM or less is ideal [10], as the effects of rotation are minimized and thus locomotion and translation within the habitat is as unaltered as possible. The downside for this lower rate is that it requires an immensely larger system radius. As the radius is decreased, in order to maintain similar gravity levels the rotation rate must increase as seen in (1). Research has shown that crews are generally able to acclimate rapidly to 4 RPM. While rotational complications like the Coriolis Effect become more prominent, studies show that nearly all subjects can acclimate rather quickly with minimal effort and time, and suggest that crews who have previously trained for adaptation or been selected with this criteria in mind can do so faster than those experiencing it for the first time.

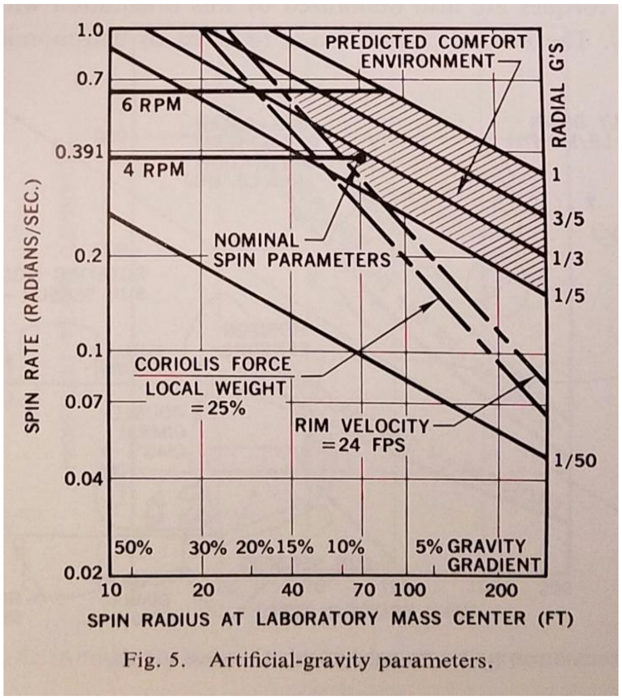

Figure 5. Chart summarizing crew comfort in rotating frames of reference

From years of experimentation, researchers found the upper limit for crew comfort without acclimation period and with the expectation of crew capability and relative comfort is generally about 6 RPM. Higher than that, the rotation rate may cause motion sickness in an increasing number of subjects, and simple translation and locomotion becomes difficult and demands extra focus. Coriolis effects can become very pronounced and many crew have a hard time doing simple tasks like touching their nose or lifting their legs in certain frames of reference.

There have been studies that show crews can work comfortably in even higher rates of rotation when given adequate time to adapt, with one particularly extensive study showing that 10 RPM was achievable with a 16-day ramp-up period [11]. This should not be used as a starting point for design, but as an extreme case of what is possible. The calculations in this proposal suggest a much more modest 3 RPM baseline rotation rate, in keeping with research findings.

Gravity Level and Rim Velocity—Studies in the 1960s at Langley Research Center established a lower bound for mobility in a partial-gravity environment at 0.28g [12]. While walking can be done at lower levels of partial gravity, translation becomes increasingly slow and difficult due to the diminished normal force, which lowers the maximum friction possible. Lower than this, subjects found it much easier to move using the skipping and bounding methods demonstrated on the lunar surface. To accommodate for this, the ceiling height in a sub-0.28g habitat may need to be raised and would likely eliminate any benefits gained from a design using very-low partial gravity.

Rim velocity measures the linear velocity tangential to the axis of rotation, and is a measure of the rotation rate and distance from the center of rotation as seen in (3). This number has a practical downside however, as some methods of mobility within a rotating frame of reference may actually be detrimental if they are not bounded properly at the conceptual level. For example, if a person were in a small rotating station undergoing 0.37g (Mars gravity) and it were sufficiently small, when the crew member walked quickly in the direction of motion counter to the direction of rotation, the vectors would partially cancel and the sum of these values could easily drop the resultant acceleration below the 0.3g threshold, making any faster movement impossible. For this reason, especially for partial-gravity designs, a minimum tangential velocity of twenty-four feet per second (7.3 meters per second) has been suggested as a guideline for a lower-bound tangential velocity.

Gravity Gradient—Research has shown that movement within a rotating frame of reference, especially rapid head movements, can be especially nauseating and disorienting for high rates of rotation in small radii. As such, an upper bound of 8% gravity gradient has been established in much of the literature as an absolute maximum. This is more useful in short-duration studies as with aircraft maneuvers and will likely not drive habitat design, as it is often overshadowed by restrictions listed above and long-term crew comfort levels.

6. LIMITATIONS OF UTILITY

There are two very significant hardware decisions to be made in the near term that will influence the viability of this proposed design: the propulsion method for TMI/TEI and the DST habitat orientation.

Propulsion Stage—A Solar-Electric Propulsion (SEP)/Chemical "Hybrid" system and a Nuclear Thermal Propulsion (NTP) engine design both still occupy the tradespace in addition to the Methane/LOx chemical propulsion stage mentioned throughout this paper. While each has their benefits, risks, and technology drivers, this paper does not seek to debate the merits of any over the others. However, it is important to note that this design does seem to favor a chemical stage, as the countermass is stable and detachable. In the earliest MSC studies, it was assumed that the habitat and SEP/Hybrid tanks would be a single integrated unit launched together, which would be impossible to use in an artificial gravity configuration. The most recent updates seem to indicate that the masses for each will force them to be built separately and mate in orbit. If this assumption is maintained going forward, then SEP/Hybrid may prove to be an applicable propulsion stage as a countermass as well.

Habitat Orientation—Habitats designed for artificial gravity must also have floors oriented perpendicular to the radius of rotation. As such, this design is conducive to vertically-oriented habitats, with decks separating segments.

Translation between these floors via ladders will be potentially hazardous with small-radii designs, as tangential forces change fairly rapidly with changes in radius (climbing and descending). As such, it will likely be necessary to have a ladder facing toward the direction of rotation for "down" translation, and another facing the opposite direction for "up". In this way, the tangential forces will always push the crew member toward the ladder, never away. This may be mitigated if the design calls for a "ship's ladder" design of sufficient length. Additional safety measures for openings, such as railings, will likely be important as well.

7. ARTIFICIAL GRAVITY OPPORTUNITIES

There are a variety of health, crew comfort, and hardware complexity issues that missions have to balance each time crew is sent into microgravity, many of which can be addressed or eliminated by introducing an artificial gravity environment. The following list represents just a few of the areas where this design may prove to be a benefit:

Crew-to-Surface Pre-Acclimation—By spinning up only once inserted into Martian orbit, the crew can be reintroduced the crew to gravity slowly, yet for as long as is necessary to fully acclimate them to its effects and ensure their condition prior to landing on the surface. Even though this pushes additional crew time onto the Transit Habitat, this represents no additional mass as the habitat must carry supplies and spares for a full surface abort anyway.

Orbital-Only Missions—Early missions may choose to fully insert into Martian orbit as part of the incremental plan culminating on surface landing. During this mission type, once the insertion burn has happened, the crew must dock with the pre-supplied return stages and remain in Martian orbit for the full duration until the next Earth-return window, usually around 500 days. This represents a full 950-1150 days in microgravity, nearly triple the currently-established maximum any space program has attempted.

By implementing this design as an option, the orbital-only crew could spin up to 0.37g upon reaching its ideal Mars orbit, and spend that 500-day segment in a Mars-analogue gravity environment, which would better allow for research, planning, and setting of expectations with future landed missions.

Surface Abort—In the unlikely scenario where the crew lands and is unable to stay on the surface for the full-duration, especially in an immediate return-to-orbit scenario where crew mobility is paramount from the moment they land, this would allow for the crew to be fully capable of any contingency thrown at them.

Short-Term Crew Health—One of the biggest concerns for interplanetary travel is physical and vestibular sensorimotor deterioration that occurs in prolonged exposure to microgravity. A single fall during an EVA from muscle fatigue or imbalance could lead to fractures, head trauma, muscle tears, ligament damage, or even life-threatening damage to the crew member's space suit or Personal Life Support System [13].

Long-Term Crew Health—One of the biggest concerns of long-duration spaceflight is how to maintain the health of the crew for long periods in such hostile environments. The physical concerns already noticed by returning astronauts include and are not limited to the following [13], each of which would be allayed if not eliminated by re-establishment in a controlled gravity environment:

1) Vision alterations like nystagmus
2) Increased intracranial pressure
3) Renal stone formation
4) Sensorimotor alterations
5) Bone fracture
6) Back pain
7) Cardiac rhythm irregularities
8) Reduced aerobic capacity
9) Effectiveness of exercise regimen
10) Urinary retention
11) Orthostatic intolerance
12) Effects of medicine
13) Intervertebral disk damage
14) Isolating causes of DNA / telomere mutations

Crew Comfort & Performance—Simple tasks are done more methodically in microgravity as bracing and countermotions must be accounted for. Additionally, simple comforts like showers can be offered again.

Fire Suppression—Fire in space is one of the biggest concerns when it comes to crew safety, as it can be very difficult to control, anticipate, and extinguish. There was a fire on Mir which took at least 90 seconds to fully extinguish, with one astronaut claiming it lasted a full 14 minutes, and with smoke that didn't clear for 45 minutes [14]. Within a gravity field, even an artificial one, thermals and a specified "up" for fire propagation can be anticipated, and the control systems established to better combat them.

In-Space Manufacturing—The ability to create as similar an environment to Earth could result in a higher-fidelity parts when machining or creating components via additive manufacturing. The addition of these "off-the-shelf" capabilities without the need to alter their design and performance may mean repairs and manufacture of replacement parts in Mars orbit will diminish the required number of spares sent from the Gateway during each mission.

Scientific Research—By utilizing a multi-floor habitat design, scientific payloads could be established at each floor level or at specific gravity locations for simultaneous research of partial-gravity effects.

Carbonated Beverages—Creature comforts are often the most missed components of spaceflight, and while the reintroduction of a gravitational environment will still not allow for charcoal barbeques, it could allow for other comforts like soda which are notoriously difficult to drink in microgravity. It might even allow for the sending of a bottle of bubbly to celebrate Mars arrival.

8. Architecture Components

The original proposal for this concept was MORL, which included a 56m^3 pressurized habitat/laboratory with a spent upper stage, later upgraded with the Apollo Concept II to 159m^3.

Habitat—As mentioned briefly in the previous section, the habitat orientation will play a significant part in whether a design is viable for in-space artificial gravity applications. Habitats that are designed with segmented floors in the vertical orientation (like Skylab, for example) can align directly with the loading paths, whereas designs that segment the pressure shell in a horizontal orientation create a significant problem with how and where to couple the cable system. Therefore, a design like the MSC habitat is already well-suited for use in this application and can be easily adapted.

Center of Rotation (COR) Ring—The COR ring and its mechanisms are the only new pieces of hardware proposed in this paper. This ring, similar to the one seen on the MORL design in Fig. 3, will house a redundant array of winches along its inner radius for tethering to both the habitat and stage.

The cable and winch system will be used during spin/despin to expand to full rotational length, as well as for use in making minor adjustments during daily operations as the crew move about within the cabin and shift the center of mass. This ring will house a docking system for attaching to the TEI stage and the cable ends will be either affixed via docking method design or physically attached during a deep-space EVA.

Solar Arrays—The solar array truss systems will be attached to the outer diameter of the connecting ring via a Solar Alpha Rotary Joint (SARJ) similar to the design currently flown on the ISS, and this will be used to ensure solar pointing throughout the rotation phase. These solar panels will be very large, so the induced forces placed on them will be kept at a minimum if the COR ring is able to maintain its position at the system's center of rotation to the extent possible. These arrays will extend from the ring after launch, and pose little design change as the current MSC design already has them positioned on the forward skirt.

Communications—During the transit period, the MSC plans for either a large dish or laser communications for high gain, high amplification data transfer for maximum bandwidth, but each of these requires a fine focus to ensure a constant data stream. This becomes complicated by inducing rotation. For the rotational acclimation period, it may be necessary to switch to a lower-bandwidth option like phased arrays, which already are in use and have been applied to modern space and military applications, but would be potentially much more conducive to a rotating environment. This would mean a potential decrease in uplink/downlink bandwidth unless a system could be devised to countermand the motion effects. A higher refinement of this design in future studies will look into the compound error propagation effects of having a dish with a pointing mechanism attached at the end of the solar array truss, and whether this higher transmission rate in both micro- and artificial-gravity modes can still be anticipated.

Stage Mass—In the MSC design, the Methane Cryogenic Propulsion Stage (MCPS) are approximated to be nearly the exact same mass as the fully-outfitted habitat. Because of this near-symmetry, their center of rotation is offset by the center of the cable system by less than 2 meters. This serves to simplify the cabling and winch requirements, as both sides of the connection ring can be identical systems and similar lengths.

9. Spin-Up and Spin-Down Procedure

Propellant Mass Requirement—Because this design requires a spin/despin via mass-transfer, this paper will run through a few rough calculations to determine a conservative estimate of the propellant needed to do so. Starting with the mass fraction equations from the rocket equation:

$$\Delta v = -v_e ln \frac{m_f}{m_0}$$

$$v_e = g_0 I_{sp}$$

Defining the mass of just the propellant:

$$m_f = m_0 - m_{prop}$$

Then rearranging the equation to just solve for the mass of the propellant results in a final equation:

$$m_{prop} = m_0 \left(1 - e^{\frac{-\Delta v}{I_{sp} g_0}}\right)$$

Some of the previous designs for the MSC habitat already include RCS systems for the habitat, specifically R-4D engines arrayed in four clusters of three engines both fore and aft, so this will be used for this reference calculation. These use an MMH/NTO system with a 1.65 mixture ratio, which yields an I_{sp} of about 312 seconds. A 3% "ullage" tankage excess is also included. Therefore, the fuel each spin/despin maneuver requires can be found as:

$$m_{prop} = 108500 \left(1 - e^{\frac{-13.3}{312*9.81}}\right)(1.03)\ [kg]$$

$$m_{prop} \cong 485\ [kg]$$

$$\cong 1069\ [lbm]$$

If the habitat and stage both are outfitted with two engines fore and two engines aft, this propellant is burned nearly evenly across the system. With the R-4D flow rate of approximately 0.14 kg/s, an estimated total spin/despin time is established:

$$\frac{485}{(0.14)(8)} = 433.0\ [s]$$

Each maneuver therefore will require just over a seven minute total burn, considerably less than the hour of continuous burn the thrusters are rated for and only about 1% of their 40,000 second total rated lifespan. This spin will result in an average of 0.38g within the habitat itself, (~0.34g in the upper floor, ~0.42g in the lower) at 3RPM.

There have been some efforts to standardize onboard fuel to a single fuel type, rather than separate tank and supply systems for the traditional cryogenic main engines and thruster systems. If this proves fruitful, the amount of propellant necessary to spin-up and spin-down will decrease significantly, as cryogenic thrusters generally have shown a higher specific impulse and both systems will share the same ullage requirement.

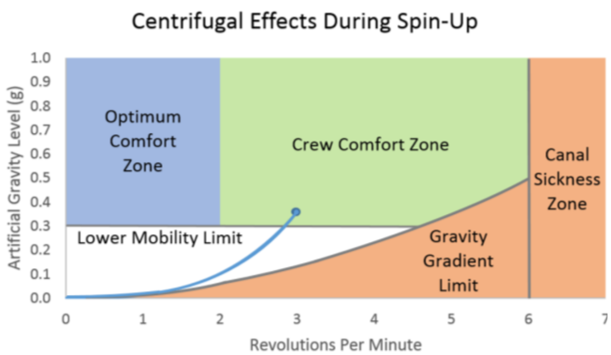

Figure 6. An example spin-up scenario, where the rate of cable extension and the increasing rate of rotation are held constant, after an initial 0.05 RPM spin to pre-tension the cables

Spin-Up and Spin-Down Procedure & Timeline—Expansion of the cabling and firing of the thrusters should be done after extensive testing to ensure crew comfort and predictable expansion process. Both systems should be designed to work together to remain within desired design parameters and crew comfort parameters.

The most mass-efficient method would be to start the system into rotation with the cables fully retracted, and slowly begin to deploy as thrusting continues. This minimizes the need to do opposition thrusting to maintain distance if the cables were deployed first.

With a small initial rotation, even less than 1 RPM, the habitat and MCPS will begin to undergo centrifugal force, enough to create tension on the cable as it deploys but with a slow enough rotation to only effect a slight g-load on the crew.

As it is likely the crew has been in microgravity for a significant amount of time before this maneuver, it is assumed for the purposes of this paper that they would be in their crew quarters laying supine and the maneuver would either be entirely self-regulated or one crew member would be positioned in a semi-reclined seat to maintain controls.

There are a wide combination of deployment variables that will lead to a satisfactory spin/despin scenario, but a likely focus may be to hold thrust and cable length expansion rate constant for practical purposes. Figure 6 demonstrates how that deployment would look as compared to the initial-spin design requirements listed in the sections above.

Long-Term Stays Using Acclimation—Whether a long-term stay is part of the planned mission like the early orbital missions, or unplanned like an undiagnosed MDV failure or surface abort, there are distinct possibilities for slowly ramping up to higher-g loads over a longer elapsed time than mentioned above. This would not be for mere acclimation to Mars gravity, but as an attempt to mitigate the damage caused by long-term microgravity. This can be done within the existing fuel requirements and has been shown to be feasible in a variety of tests.

By merely reducing the length of the tethers, the rate of rotation will increase and cause the apparent gravity levels to climb as well. As discussed above, there is a limit to what crew can easily and quickly acclimate to, but demonstrations have been done which show that crew can maneuver and work without discomfort in as high as 10 RPM when given an acclimation period of at least sixteen days. If the stay were anticipated to be nearly the full 500 days, it would likely be beneficial to the crew to increase this rotation rate slowly, ensuring crew comfort, to a level higher than merely Martian gravity. For an EMC-sized configuration, Figure 8 can serve as a quick reference in this kind of analysis.

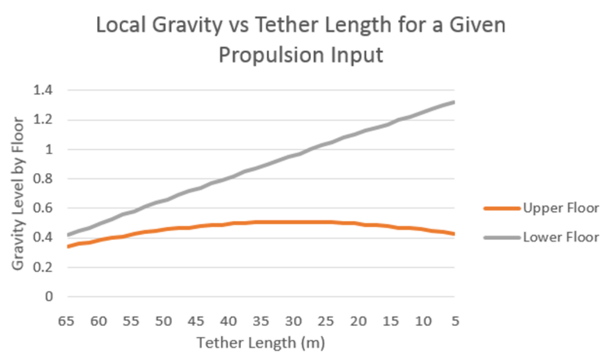

Figure 7. Demonstration of gravitational variance between floors as tether length changes. This is due to variations between the counter-mass lengths and masses, and will vary from design to design

By shrinking the radius from 110’ of cable to approximately 24’, the lower deck would reach 1g and the system would be rotating at 7.4 RPM. Note that the gravity gradient would increase due to the smaller radius, and the upper level will not exceed 0.51g due to the shrinking diameter and the slight mass imbalance between stage & habitat. Even at this extreme instance, this design is still backed up by historic data and could be implemented. More likely, a balance between loading and crew comfort would be reached closer to 5-6 RPM (maximum loading of 0.7g and 0.82g respectively).

10. Impact on Surface Architecture

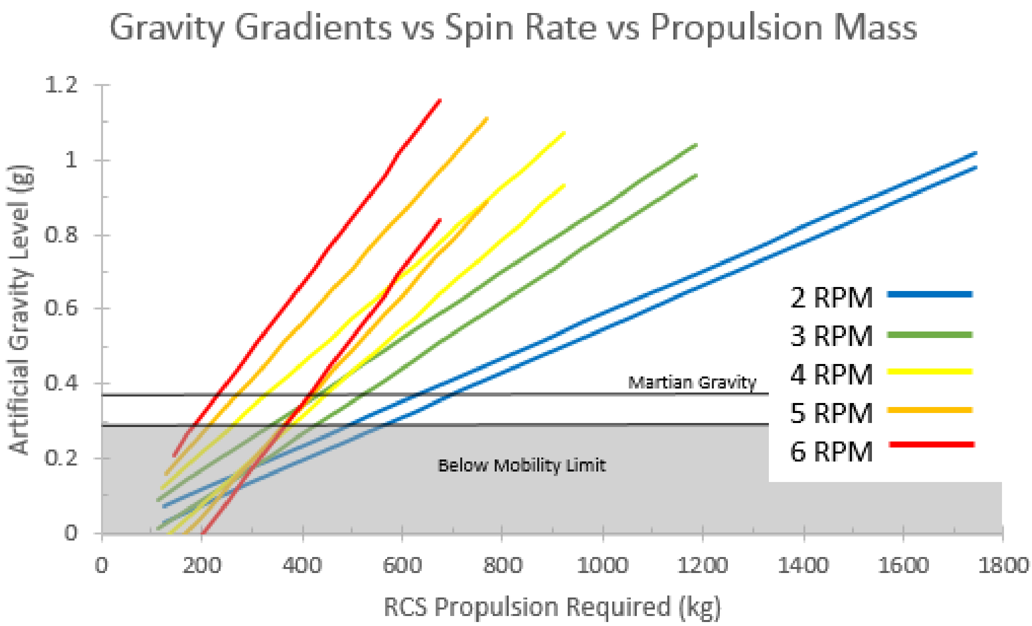

Figure 8. Correlation between g-level and the estimated RCS propellant required as a function of spin rate for an MSC/stage "barbell" system. The color bands represent the deviance between relative gravity at each deck

The additional mass of propellant (~1mt per maneuver) and hardware (COR ring) can be offset, at least significantly, by the elimination of systems whose design overlaps with this new capability. Lander structure and systems requirements can be simplified, as the landers are no longer necessary for days-long acclimation as a temporary shelter, but can be bare-bones Apollo-style landers. There is no longer a need for a massive surface power cable system to connect the Kilopower system to the lander, nor is there the requirement for the lander and surface vehicle to be able to dock together via a pressurized tunnel. Each of these systems represents a Martian surface asset that had to be landed with monolithic heat shields and retropropulsion fuel, whose mass can also be either shrunk or reallocated for other surface assets. It is difficult to state proper estimated mass added and removed without further work into exactly which systems can be removed or downsized and better refinement into to their individual masses. This is work the author will continue pursuing in future work.

11. Conclusions

Artificial gravity is compatible with microgravity flight hardware and offers significant opportunities in terms of crew health, safety, comfort, and capabilities. This paper demonstrates that it can be implemented with a focus on low-mass and high reliability, and can be made competitive by cutting mass and improving crew safety elsewhere in the mission.

Artificial gravity began as an expectation in baseline designs, but became lost from the tradespace as technology and research needs dictated design. Now, we stand at the brink of a new Space Age, where reaching into the unknown and more hazardous will put a distressed crew months from rescue. We must look at design capabilities and adapt a new outlook on the limitations of technology and biology, and examine all options for decreases in mass, time, and cost, while keeping crew safety and long-term health paramount.

> *"The enduring problem with designing for artificial gravity at this point in history is that, no matter what you propose, 'more research is needed' to validate it."*
> \- Dr. Theodore Hall

Committing to an artificial-gravity space station design would utilize existing research and encourage more, furthering our understanding of long-term self-reliance and crew health as we prepare for exploration beyond LEO and pave the way for what lies beyond.

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REFERENCES

[1] K. Tsiolkovsky, in *Dreams of Earth and Sky*, 1895, p. 108.

[2] W. V. Braun, "Man Will Conquer Space Soon," *Collier's Magazine,* pp. 22-74, March 1952.

[3] *Challenge of Outer Space.* [Film]. UAH Salmon Library, 1955.

[4] J. Hansen, Spaceflight Revolution, Auburn, AL: NASA Langley Research Center, 1955.

[5] W. V. Braun, "Man Will Conquer Space SOON," *Collier's*, 22 March 1952.

[6] A. Pisciotta, "NASA Technical Reports Server," Douglas Aircraft Company, January 1966. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19670010837.pdf. [Accessed 1 10 2018].

[7] M. R. a. J. Connolly, "Deep Space Gateway - Enabling Missions to Mars," 2018.

[8] e. a. Tara Polsgrove, "Transit Habitat Design for Mars Exploration," *AIAA Space,* 2018.

[9] e. a. Bret Drake, "Human Exploration of Mars Design Reference Architecture 5.0," NASA Johnson Space Center, Houston, TX, 2009.

[10] R. R. Gilruth, "Manned Space Stations - Gateway to our Future in Space," in *Manned Laboratories in Space*, New York, NY, D. Reidel Publishing Company, 1968, pp. 1-10.

[11] NASA Historical Staff, "Astronautics and Aeronautics, 1965," NASA, 1965.

[12] A. B. Thompson, "Physiological Design Criteria for Artificial Gravity Environments in Manned Space Systems," in *Symposium on the Role of the Vestibular Organs in the Exploration of Space*, Pensacola, FL, 1965.

[13] Human Research Program - Human Health Countermeasures Element, "Evidence Report: Risk of Impared Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Spaceflight," NASA JSC, Houston, TX, 2016.

[14] B. Burroughs, Dragonfly: NASA and the Crisis Aboard Mir, London: Fourth Estate, Ltd, 1998.

BIOGRAPHY

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