Variable Gravity Laboratory for Deep-Space Crewed Missions Research and Demonstration

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This paper describes a Variable Gravity Laboratory (VGL) in Low Earth Orbit (LEO). VGL produces Luna-to-Mars gravity levels by variable-rate centripetal acceleration. The VGL comprises a Docking Hub Module (DHM) on the VGL rotation axis, and two opposed Spin Gravity Modules (SGMs), each connected to the DHM by two inflated Tension Tubes, which tether the SGMs to the DHM, and provide redundant Crew access between the DHM and each SGM. All three Modules have life support capability, so the VGL is triply redundant in life support for crew safety on long-duration missions. The VGL is placed into a Dawn/Dusk Sun-Synchronous LEO in three medium-lift launches, one for each Module. The VGL rotation axis is normal to the orbital plane, so that one end of each Module is hot in constant Sunlight, the other end cold in constant darkness, to enable combined thermal and photovoltaic electricity generation. The VGL provides the gravity levels required for flight qualification of gravity-enabled systems for Luna and Mars surface habitation, and to demonstrate a spin-gravity spacecraft, electric power, thermal. and life support architecture for crewed transit to and from Mars and near-Earth asteroids. The VGL provides essential data on long-duration effects of Luna and Mars gravity levels on humans, food plants, and gravity-enabled equipment, including minimum gravity level required to prevent human hypogravity deconditioning. If humans are going to establish a Lunar Base, explore Mars, and eventually settle on Luna and Mars, it is essential that such gravitational response data be acquired first. The VGL is a practical way to do this.

Nomenclature

α = centrifugal acceleration
ε = radiant emissivity
ρ = tether density
σ = Stefan-Boltzmann constant
ω = angular velocity
A = tether cross-section area
f = rotation rate
F = tether tensile force
g = gravitational constant
I_S = specific impulse
m = tether mass
M_1 = initial module mass
M_2 = final module mass
Q = radiant heat flux
R = rotation radius
S = ultimate tensile stress
T = temperature
V_T = tangential velocity

I. Introduction

From thousands of hours of human experience in Low Earth Orbit (LEO), the effects of long-duration human exposure to microgravity are known, especially cardiovascular deconditioning and osteoporosis. From the six Apollo Lunar missions, a small amount of data exist on human short-duration response to Lunar gravity. No data exist for long-duration human response to Lunar gravity, or for short-duration or long-duration human response to Mars gravity. Also, insufficient data exist to determine the minimum gravity level required to prevent human deconditioning. If humans are going to establish a long-duration Lunar Base, explore Mars and near-Earth asteroids, and eventually settle on Luna and Mars, it is essential that such human-gravitational-response data be acquired.

Before humans embark on deep-Space missions, with long-duration transit times and long-duration surface habitation, all transit spacecraft and surface habitat systems that sustain human life must be flight qualified “in a relevant environment”[1]. While microgravity-compatible systems can be flight qualified by demonstration on the International Space Station (ISS), gravity-enabled systems intended for use on Luna or Mars must be flight qualified <u>at the gravity level of Luna or Mars</u>.

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This paper describes a Variable Gravity Laboratory (VGL) in LEO to test the effects of Luna-to-Mars gravity levels on organisms and machines. The VGL produces "spin-gravity" by rotation-induced centripetal acceleration. The VGL comprises a Docking Hub Module (DHM) on the rotation axis and two opposed Spin Gravity Modules (SGMs), each connected to the DHM by two inflated Tension Tubes, which tether the SGMs to the DHM and provide redundant Crew access between the DHM and each SGM. Air pressure hoop and plug loads in the Tension Tubes keeps them rigidly in tension, so the VGL is structurally stable, even at zero spin rate. Hatches in the Modules exist to isolate the Modules and Tubes from each other in the event of a fire or air leak to Space vacuum. With life support capability in each module, the VGL is two-fault tolerant (triply redundant) for life support capability failure.

The VGL is placed in a Dawn/Dusk Sun-Synchronous LEO in three medium-lift launches, one for each Module. The VGL rotation axis is normal to the orbital plane, so that one end of each Module is hot in constant Sunlight, and the other end cold in constant darkness, to enable combined photovoltaic and thermal electricity generation.

The VGL provides essential data on the effects of Luna and Mars gravity on humans, food plants, and gravity-enabled equipment, especially life support systems. The microgravity-compatible air and water recycle systems currently used on ISS have insufficient performance and reliability for use on deep-Space missions, far from sources of consumables and spares resupply. Gravity-enabled, commercially-available life support processes and equipment have the extremely high levels of performance and reliability required for deep-Space missions. The VGL provides the gravity levels required for flight qualification of gravity-enabled systems for Luna and Mars surface habitation systems. Finally, the VGL itself enables flight qualification of a spin-gravity spacecraft, power, and life support architecture for crewed transit to and from Mars and near-Earth asteroids.

II. VGL Orbital Architecture

Figure 1 depicts the Orbital Architecture of the Variable Gravity Laboratory, with relationships shown among the Solar Ecliptic Plane, VGL LEO Plane, and VGL Rotation Axis. The VGL is placed in a Dawn/Dusk Sun-Synchronous LEO, an orbit whose plane rotates once yearly, always above the dawn/dusk terminator of the Earth, so that the VGL is always in Sunlight, just as a crewed Spacecraft would be during a deep-Space transit mission. Therefore, the VGL can flight qualify power and thermal architecture for deep-Space crewed transit missions. Since Earth has an axial tilt of 23.5 degrees with respect to the Solar Ecliptic Plane, the VGL orbit has 66.5 degrees inclination, higher than the 51.6 degrees inclination of ISS, but far from a polar orbit.

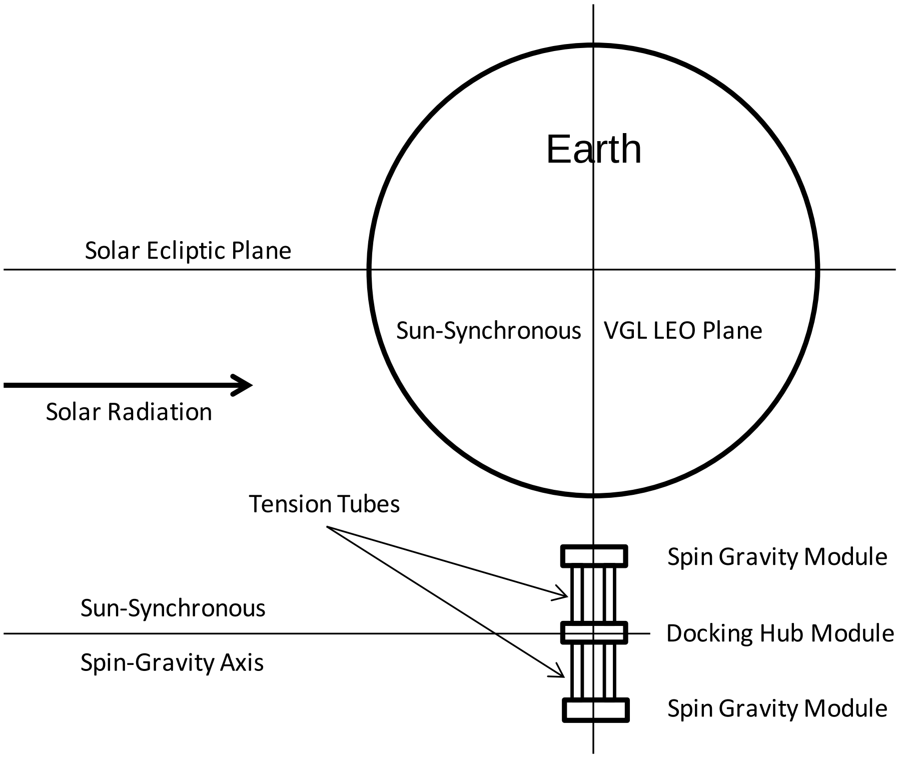

Figure 1. VGL Orbital Architecture

Figures 1 and 2 show that the VGL comprises a Docking Hub Module and two Spin Gravity Modules, with SGMs connected to DHM by inflated Tension Tubes that tether modules together and provide redundant crew access among Modules. Air pressure hoop and plug loads in the Tension Tubes keep them in tension, so VGL is structurally stable, even at zero spin rate. Hatches in Modules isolate Modules and Tubes from each other in the event of fire or air leak. With life support capability in each Module, VGL is two-fault tolerant in life support for crew safety. The DHM is similar to an ISS U.S. Node, a rigid cylindrical module with ISS-standard docking ports on each end, so two crew vehicles, or one crew vehicle and one cargo vehicle, can simultaneously dock to the VGL. A docking vehicle aligns, both in translation and attitude, with VGL rotation axis through DHM center, then rolls to match VGL rotation rate and DHM docking alignment. Since the VGL docking maneuver has the same number of degrees of freedom as an ISS docking maneuver, it should be no more difficult to dock to the VGL than the ISS.

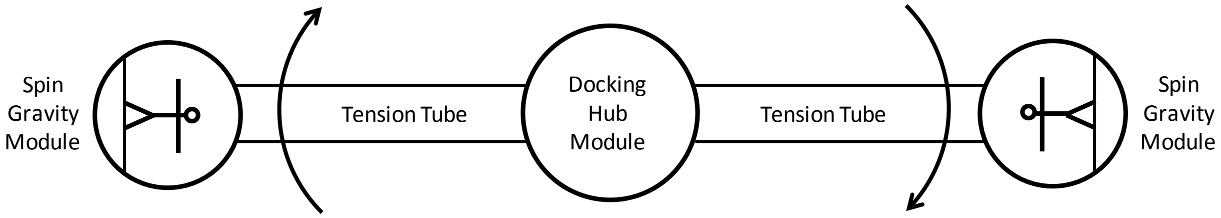

Figure 2. VGL Module and Tension Tube Configuration

The centrifugal force induced by VGL rotation induces "spin gravity", the level of which is determined by VGL rotation rate and tether length, in accordance with the Newtonian angular acceleration equation

$$\alpha = R\,\omega^2 = R\,(\,2\pi f / 60\,)^2 \tag{1}$$

where α is centrifugal acceleration, R is rotation radius, ω is angular velocity, and f is rotation rate in rpm. Prior research[2] has shown that humans readily adapt to rotation rates of up to three rpm after two days in a spinning room. With a rotation rate of three rpm, VGL rotation radii are 37 m and 16 m for centrifugal accelerations of 3.7 m/s^2 (Mars gravity level) and 1.6 m/s^2 (Luna gravity level), respectively. With 37 m rotation radius, two rpm and three rpm produce Luna and Mars gravity levels, respectively.

Propellant mass needed to achieve desired VGL rotation rate is determined by the Rocket Equation

$$\ln\,(\,M_2 / M_1\,) = -\,V_T / (\,I_S\,g\,) \tag{2}$$

where M_1 is Spin Gravity Module mass before rotation, M_2 is SGM mass after rotation, V_T is SGM tangential velocity, and I_S is the spin rocket specific impulse. At three rpm and 37 m rotation radius, SGM tangential velocity is 12 m/s. With typical rocket engine propellant specific impulse of 300 s, SGM mass ratio M_2 / M_1 is 0.996, so <u>propellant mass needed for VGL rotation is insignificant relative to Spin Gravity Module mass.</u>

The tether tensile force F that a Tension Tube has to withstand is a product of Spin Gravity Module mass M_2 after rotation and SGM centrifugal acceleration.

$$F = M_2\,\alpha / g \tag{3}$$

Tension Tube material cross-section area A is a ratio of tether tensile force and Tension Tube ultimate tensile stress S (safety factor of four added).

$$A = 4\,F / S = 4\,M_2\,\alpha / g\,S \tag{4}$$

Tension Tube mass m is a product of tether length, cross-section area, and tether material density ρ.

$$m = 2\,R\,A\,\rho = 8\,M_2\,R\,\alpha\,\rho / g\,S \tag{5}$$

Equation (5) can be solved for the ratio of Tension Tube mass to Spin Gravity Module mass.

$$m / M_2 = 8\,R\,\alpha / g\,(\,S / \rho\,) \tag{6}$$

The Tension Tube is made of high performance pyrolytic-graphite or tensilized-polyethylene fabric, both materials having mass-specific strength S/ρ of about 3.5 GPa/(g/cm^3). For Mars spin-gravity level, the ratio of Tension Tube mass to Spin Gravity Module mass is about 0.03 percent, so <u>Tension Tube mass for tethering is insignificant relative to Spin Gravity Module mass</u>.

III. VGL Spin Gravity Module Architecture

Figure 3 depicts the Architecture of the VGL Spin Gravity Module. SGM shape is cylindrical, with ellipsoidal or hemispherical ends, and with the cylinder axis parallel to the VGL rotation axis. This shape and orientation, combined with the VGL orbit, create unique advantages relative to other Spacecraft architectures.

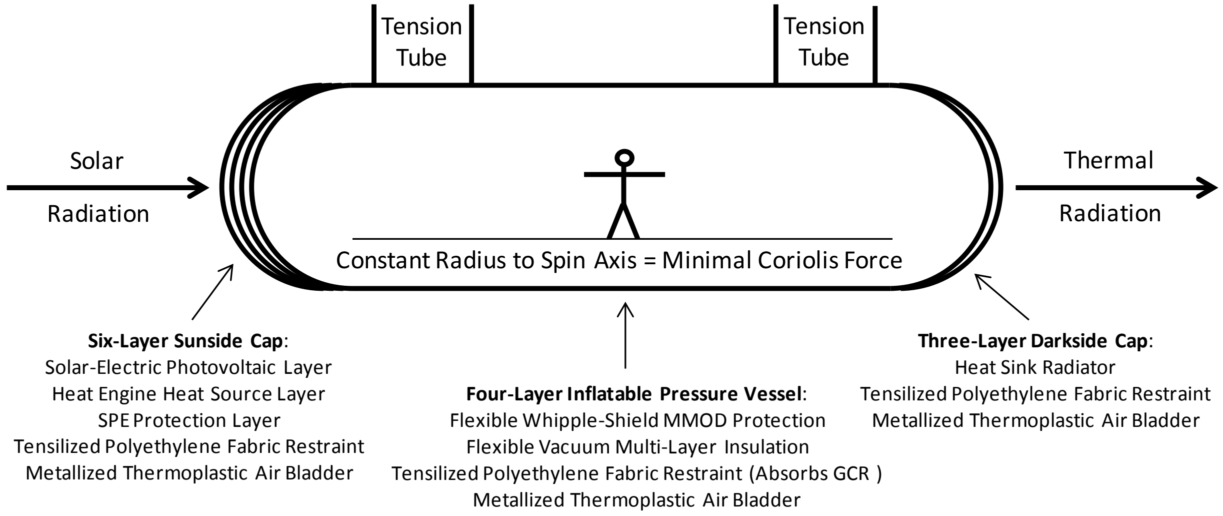

Figure 3. VGL Spin Gravity Module Architecture

The SGM is a "single-story" dwelling, so that crew translation within the SGM occurs at a constant rotation radius, thereby minimizing Coriolis Effect on crew vestibular performance. Combined with low VGL rotation rates, disturbance of the human vestibular system by Coriolis Effect should be almost unnoticeable. One end of the SGM cylinder always points at the brightness of the Sun, and the other end at the darkness of deep Space. So the Sunward end gets hot, and the darkward end gets cold. This creates a large temperature difference between the ends, suitable for thermal power production. With photovoltaic panels and heat engine source covering the Sunward end and heat engine radiative sink covering the darkward end, a VGL Combined Photovoltaic and Thermal (CPVT) electrical power system has an overall sunlight-to-electricity conversion efficiency of about forty percent of the 1400 W/m^2 Solar irradiance in Earth orbit. This conversion efficiency is based on performance of terrestrial CPVT systems[3]. Twenty percent of Solar irradiance (280 W/m^2) is converted photovoltaicly to electricity, thirty percent (420 W/m^2) is radiated as waste heat from the Sunward end of the SGM, and fifty percent (700 W/m^2) is captured by the SGM heat engine. The gravity-enabled heat engine converts forty percent (280 W/m^2) of the captured heat to electricity, and the rest of the captured heat (420 W/m^2) is radiated as waste from the darkward end of the SGM. To lower radiating temperature, the darkward radiator area is twice the Sunward radiating area. The temperatures of the SGM Sunward and darkward radiators are found using the Stefan-Boltzmann Law

$$Q = \varepsilon \, \sigma T^4 \tag{7}$$

in which Q is radiant heat flux, ε is emissivity of the radiating surface, σ is the Stefan-Boltzmann constant, and T is temperature of the radiating surface. With typical emissivities of 0.15 for the VGL Sunward end (Solar panels) and 1.0 for the SGM darkward end (blackbody radiator), and radiant heat fluxes of 420 W/m^2 from the Sunward end and 210 W/m^2 from the darkward radiator, the temperatures of the SGM ends are 470 K Sunward and 250 K darkward. This 220 C temperature difference drives the VGL CPVT heat engine, which can be an inexpensive, commercially-evolved, gravity-enabled machine rather than an expensive, custom-developed, microgravity-compatible one.

The most mass-efficient SGM pressure vessel is a fabric restraint with a metallized thermoplastic air bladder. This technology was flight qualified by Bigelow Aerospace with their well-known Genesis Spacecraft. The cylindrical portion of the pressure shell is covered with conventional MicroMeteoroid/Orbiting Debris (MMOD) shielding and vacuum MultiLayer Insulation (MLI) for puncture and thermal protection. If the SGM pressure vessel fabric restraint is made with tensilized-polyethylene fiber, it provides partial protection from Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs), since polyethylene is a very efficient absorber of high-energy particles.

IV. VGL Research and Demonstration Utilization

A. Gravitational Biology

From thousands of hours of human experience in LEO, the effects of human exposure to microgravity are known. For short-duration missions (up to two weeks), such as Space Shuttle flights, humans experience mild cardiovascular deconditioning and moderate vestibular system dysfunction, including loss of balance and kinesthetic sense. For long-duration missions, such as Russian Mir and ISS expeditions, cardiovascular deconditioning and vestibular dysfunction are more severe, and can only be partially mitigated with a time-consuming exercise regimen. Little can be done to mitigate the slow but constant rate of osteoporosis induced by living in microgravity. The only data available on human response to partial gravity levels are from the six short-duration Apollo Lunar missions. Exposure duration and number of humans exposed were too scant to show a definitive difference between human responses to microgravity and Lunar gravity.

So knowledge in the field of human gravitational biology is bimodal; huge amounts of data at Earth-normal gravity, a respectable amount of data, mostly discouraging, in microgravity, and almost nothing in between.

The Variable Gravity Laboratory provides, for extended periods of time, any chosen gravity level between Luna and Mars surface gravity. Data on human long-duration response to Luna and Mars gravity levels, combined with existing data on long-duration response to Earth-normal gravity and microgravity, allows gravitational biologists to “fill in the gaps” and be able to predict human response to any duration and level of gravity up to Earth-normal. They can also determine the minimum gravity level needed to prevent human hypogravity deconditioning, without the intervention of extraordinary exercise or diet regimens.

Of equal interest to gravitational biologists is the response of crop plants to Luna and Mars gravity levels. Long-duration crewed missions on Luna or Mars require Controlled Environment Agriculture (CEA) to minimize logistics penalties for food supply from Earth. The effects of Luna and Mars gravity levels on crop germination, growth, and seed production must be understood in order to design CEA systems for use on Luna or Mars. The VGL provides the means to understand long-duration response of crop plants to Luna and Mars gravity levels, and to selectively breed crop plants for Luna and Mars CEA.

If humans are going to establish a long-duration Lunar Base, explore Mars, and eventually settle on Luna and Mars, it is essential that the long-duration responses of humans and food plants to Luna and Mars gravity levels be understood before such missions are attempted. The Variable Gravity Laboratory provides the means to acquire such essential gravitational biology data.

B. Gravitational Engineering

In the microgravity of orbital Space, all systems that manage fluids and solids are penalized by having to replace the functionality that gravity provides with other means. Gases don’t rise, and liquids don’t fall, so rotary-inertial machines must be used to separate gas and liquid. Food and drink tend to float, so significant mass and volume penalties exist for storage, preparation, consumption, and waste management of food and drink in single-serving containers. Significant mass and volume penalties exist for supply and waste management of disposable clothing and towels, since microgravity-compatible washers and dryers don’t exist. The management of human bodily solid waste is particularly onerous in microgravity.

Surface gravity on Luna and Mars, and spin gravity in a deep-Space transit vehicle, allow use of any of the gravity-enabled processes and equipment used here on Earth to perform Spacecraft functions. Table 1 below lists many Spacecraft functions that benefit from the presence of gravity, and the benefits derived therefrom.

Overall, the greatest benefit of gravity-enabled processes and equipment for long duration deep-Space missions is that such technologies, highly evolved over centuries of commercial competition here on Earth, have the proven high performance, high reliability, and low cost that only mass production with statistical quality control can provide. Gravity-enabled, commercially-available processes and equipment have the high levels of performance and reliability required for deep-Space missions, and can be demonstrated and qualified with minimal development cost.

Before humans embark on deep-Space missions, with long-duration transit times and long-duration surface habitation, all transit spacecraft and surface habitation systems that sustain human life must be flight qualified “in a relevant environment”[1]. While microgravity-compatible systems can be flight qualified by demonstration on the International Space Station (ISS), gravity-enabled systems intended for use on Luna or Mars must be flight qualified at the gravity level of Luna or Mars. The Variable Gravity Laboratory provides this “relevant environment” for flight qualification of gravity-enabled systems at Luna and Mars gravity levels. The VGL also provides the environment needed to determine the effects of Luna and Mars gravity levels on gravity-enabled processes and equipment, allowing optimization of equipment performance for desired gravity levels.

Table 1. Gravity-Enabled Spacecraft Functions and Benefits

Gravity-Enabled Spacecraft Function	**Benefits of Gravity Implementation**
Thermodynamic Electricity Production	Conventional Thermal-Convection-Driven Heat Engine
Distillation Water Recycle	Highly Efficient, Reliable, and Inexpensive Commercial Still
Thermal-Convection Air Circulation	Minimize Air Circulation Fan Power
Air Humidity Removal	Highly Efficient, Reliable, and Inexpensive Condenser
Air Humidity Water Recovery	No Rotary-Inertial Air-Water Separator
Air CO2 Separation & Concentration	Conventional Temperature-Swing Liquid Scrubber/Stripper
Breathing O2 Water Electrolysis	No Rotary-Inertial Gas-Liquid Separators
Bulk Food Storage	Minimizes Food Packaging Mass & Volume Penalties
Conventional Galley	Minimizes Food Preparation Mass & Volume Penalties
Conventional Dishwasher	No Mass & Volume Penalties for Disposable Tableware
Conventional Clothes Washer	No Mass & Volume Penalties for Disposable Clothing/Towels
Washable Air and Water Filters	No Mass & Volume Penalties for Disposable Filters
Conventional Sink & Shower	No Rotary-Inertial Air-Water Separators
Conventional Urinal	No Rotary-Inertial Air-Urine Separator
Flush Toilet with Grinder	Simple Solid Waste Collection as Processable Slurry

Finally, the VGL itself can be used to demonstrate and flight qualify a deep-Space crewed transit architecture with CPVT electric power supply, spin gravity to prevent human microgravity deconditioning, and gravity-enabled processes and equipment of high performance and reliability. This Spacecraft architecture can also be used for a crewed Space Way Station located at the L1 Libration Point, gravitationally midway between Luna and Earth, as a storage, maintenance, repair, and transfer depot for crewed deep-Space missions.

V. Conclusion

The Variable Gravity Laboratory is a three-module rotating crewed Spacecraft in Dawn/Dusk Sun-Synchronous LEO. Rotation rate of the VGL can be varied to produce Luna-to-Mars gravity levels. Mass required for tethering VGL modules together, and the propellant needed to achieve desired VGL rotation rates, are insignificant relative to VGL mass. The VGL has triply-redundant life support capability for crew safety on long-duration missions.

The main purpose of the VGL is to measure long-duration effects of Luna-to-Mars gravity levels on organisms, especially humans, and the effects of Luna-to-Mars gravity levels on gravity-enabled processes and equipment, especially life support systems. The VGL can also be used to demonstrate and flight qualify gravity-enabled long-duration surface habitation systems for Luna and Mars, and a spin-gravity Spacecraft, power, thermal, and life support architecture for a crewed deep-Space transit vehicle and an L1 Space Way Station. No other near-term Space mission can provide the gravitation biology knowledge and gravitational engineering experience needed to deploy safe and cost-effective crewed deep-Space missions.

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