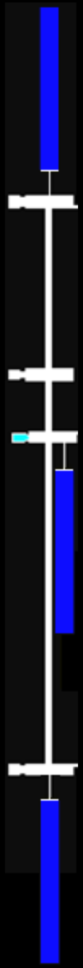
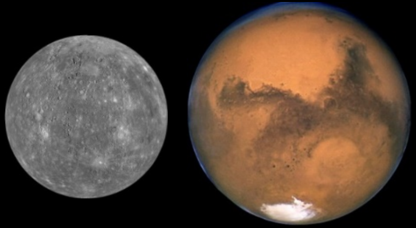




Do Humans Have a Future in Moon or Mars Gravity?

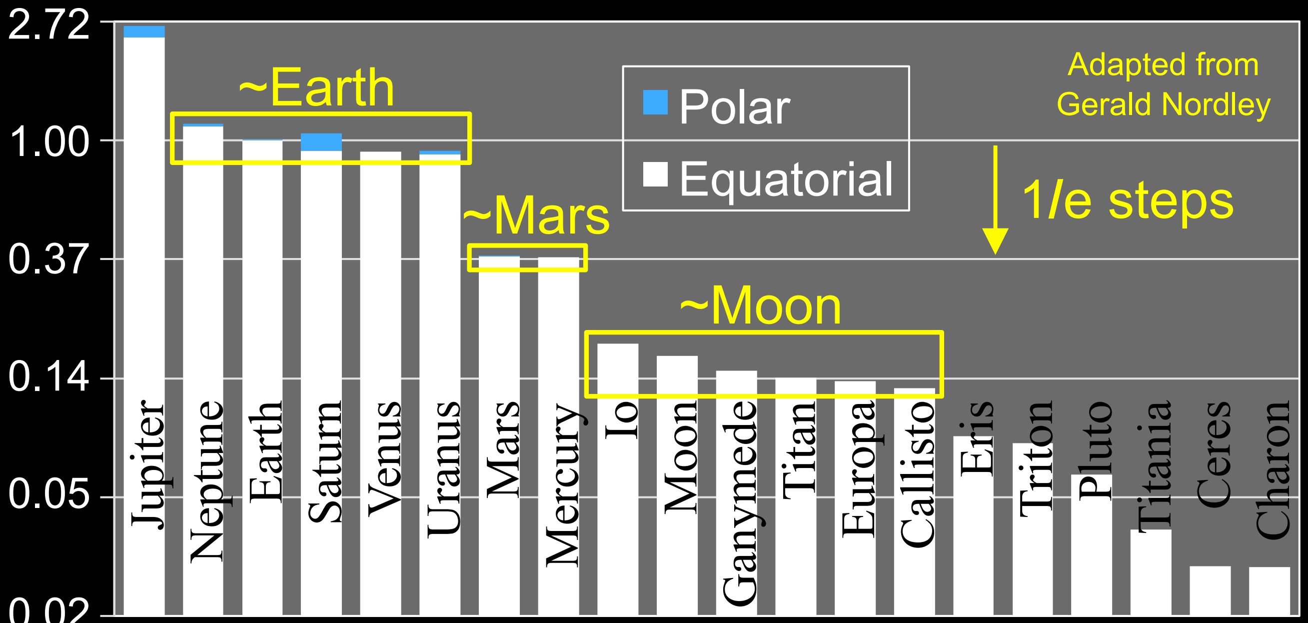
2019 IAC, Washington DC
(revised November 14, 2019)

Joe Carroll
Tether Applications, Inc.
619-980-1248 mobile
tether@cox.net

A Remarkably Convenient Coincidence

1. 4 other planets have earth-like gravity, but all 4 seem hard to colonize (now…).
2. But the 8 other places with useful gravity have just 2 levels: Mars & our Moon!

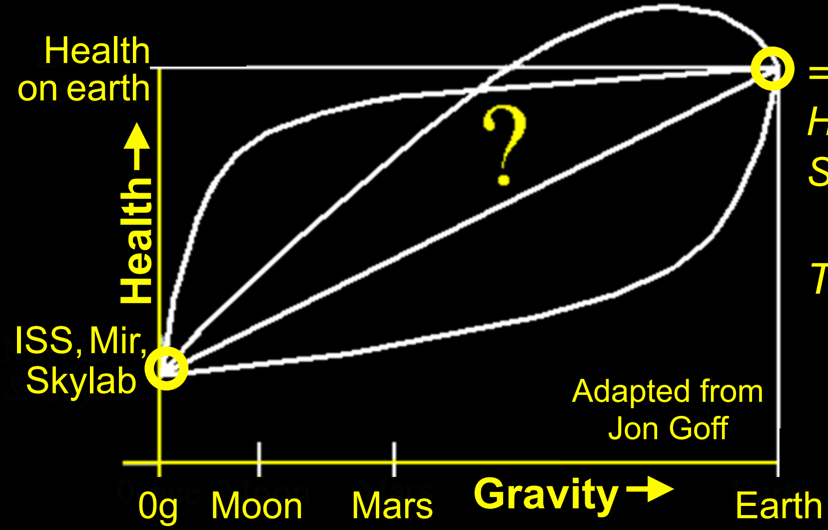
So there are only 2 gravity levels from 0.09g to 0.9g in our solar system! *Are Mars & Moon enough for our health?*



Surface Gravity Levels in 20 Large Bodies in ***Our*** Solar System

What Sustained Gravity Do Humans Need for Health?

1. All data on sustained gravity prescriptions for human health: 1= good; 0 = bad.
2. Finding out whether Moon or Mars gravity are enough will take >1 year stays!
3. Enough $$ for human exploration may depend on whether we can live there.



= Useful Data on Human Health vs. Sustained Gravity

To learn more, read Packing for Mars and Scott Kelly's Endurance.

Known Problems in Microgravity

1. Osteoporosis from calcium loss
2. Loss of heart & other muscle mass
3. 2 hrs/day vigorous exercise needed
4. Eye focus shift due to pressure
5. Immune system anomalies
6. Apparent "fast aging" effects

Most problems were found after each longer trip. What is next?

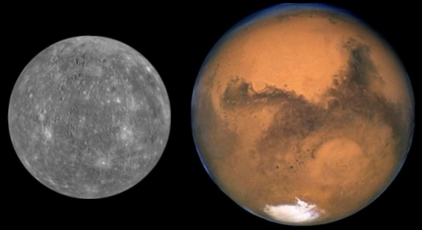
Why We Should Find Our "Gravity Prescription" in LEO

1. Both launch & return are far safer & cheaper in LEO (crew & cargo).
2. We should test gravity without insults specific to each body (eg dust).
3. We may need long tests of countermeasures like those used on ISS.
4. If our goal is settling, not exploring, we need many people, for years!

If Moon gravity is enough, we can try to live on 8 bodies:

6 largest moons, at 12-18% of earth gravity!

But if we need Mars gravity, there are 2:

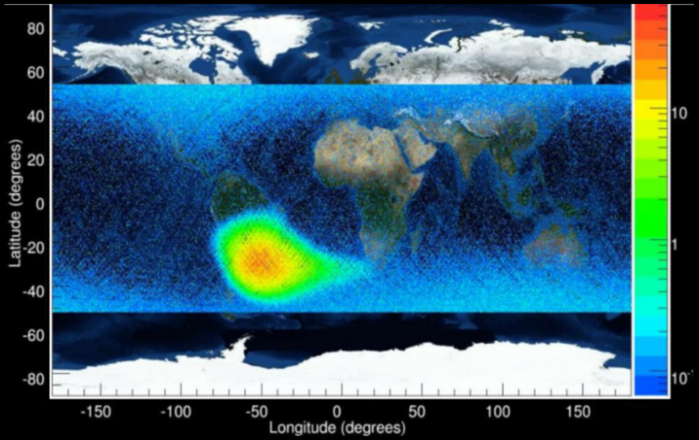


2 planets, each 38% of earth gravity!

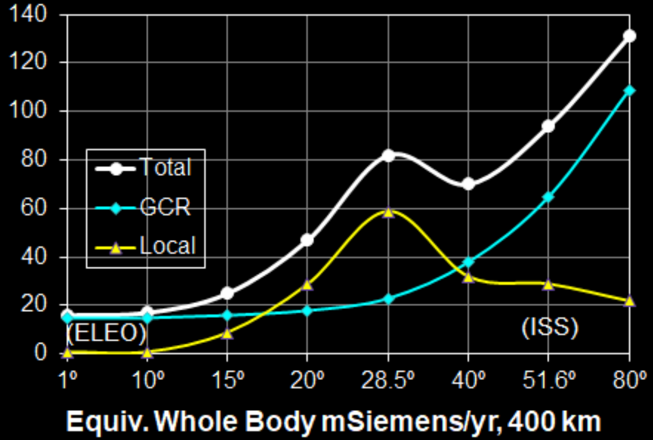
If We Find We Need >Mars Gravity, Settle in ELEO!

1. If we need >Mars gravity, we need spinning settlements in free space.
2. But we need meters of cosmic ray shielding, except in Equatorial LEO.
3. "Moon & Mars in LEO" can set gravity & size for first ELEO settlements.

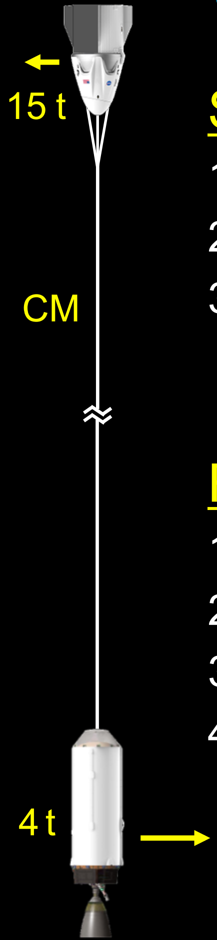
Map of Radiation Measured on ISS



Doses predicted by OLTARIS (1cm Al/Li + 10cm water, 2016)



Step #1: Gemini-like Dragon 2 Spin Sensitivity Tests



Scenario (during phasing, on crew flights to ISS)

1. Separate from stage, turn, & grab end of stowed seatbelt.
2. Dragon posigrade pulses cause spin, & raise MECO orbit.
3. Release at apogee can target deorbit of Falcon 2nd stage.

Could partial gravity ease crew adjustment to free fall?

Resembles Gemini 11 rotation test, but with:

1. 6-10X faster spin (Mars = 1.5 rpm, 148m from CM).
2. Longer & stronger seatbelt, 700m vs 30m; ~100 kg.
3. 3-point bridle & seatbelt capture device on nose cap.
4. Nose cap reinforced, & camera in nose aids capture.

Note: if a longer AG radius doesn't weigh or cost much, then use it, to allow lower spin!

Gemini 11-12 tether tests were designed after Gemini 7 crew spent 2 weeks in mg.
NASA interest was focused on low-DV station-keeping, not on artificial gravity.

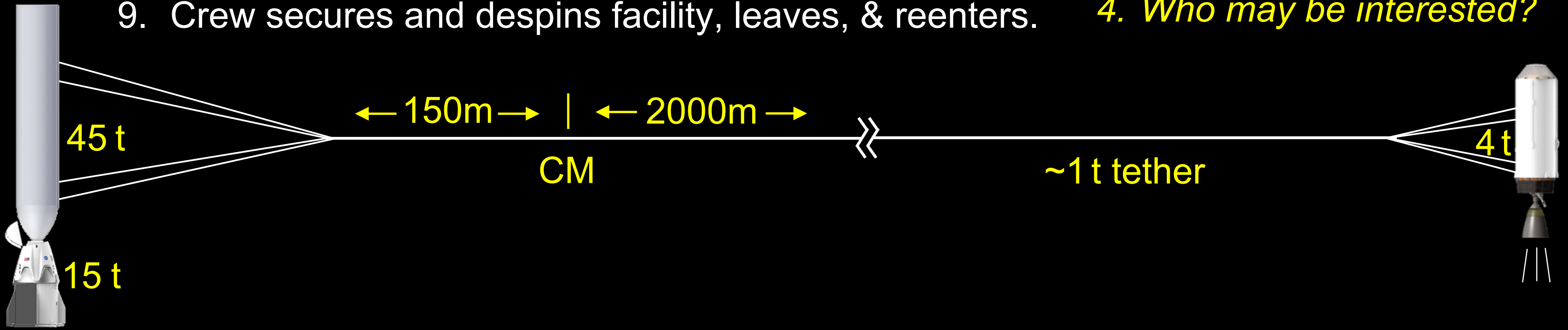
Step #2: Testing Moon-then-Mars Gravity in LEO

Possible scenario

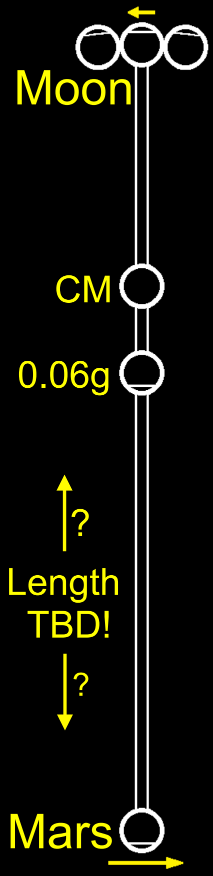
1. Launch ~45 ton facility near ISS, on Falcon Heavy.
2. Then crew launches and docks, but does not enter.
3. Falcon Heavy stage 2 leaves & pays out 2 km tether.
4. Stage starts spin-up, which peels taped bridles loose.
5. After both bridles deploy, crew enters the facility.
6. Stage does 225 m/s **D**V, for Moon gravity at 1.0 rpm.
7. Later, 115 m/s more **D**V, for Mars gravity at 1.5 rpm.
8. Months later, cut bridle to target stage + tether reentry.
9. Crew secures and despins facility, leaves, & reenters.

Four key questions:

1. Can bridles stay taped on the rocket during ascent, but then peel off reliably?
2. How long can 7 crew live in a 45-ton 200m^3 facility?
3. How should we berth new modules, for later tests?
4. *Who may be interested?*

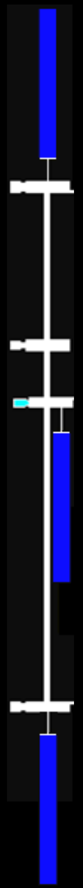


Step #3: Longer Tests of "Moon & Mars in LEO"



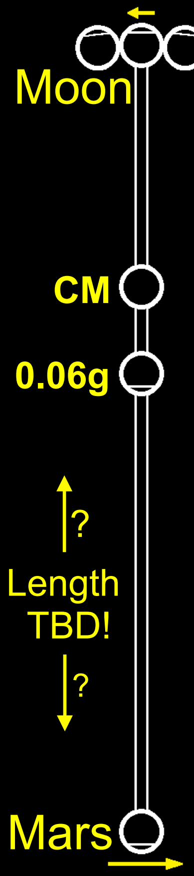
Basic Concept

1. Goal: see if sustained Moon or Mars gravity allow good human health, quicker, cheaper, better, & safer than putting crews on Moon & Mars.
2. This uses Mars & Moon modules as counterweights, not spent stages.
3. Inflatable "airbeam tunnels" allow shirtsleeve transfer between levels.
4. Earlier steps can find a suitable spin rate, which fixes tunnel lengths.
5. Access to free fall + 3 partial gravity levels may attract space tourism.
6. A module at 0.06g is the next ~1/*e* step down after earth-Mars-Moon:
   - Neal Pellis suggests that 1/e steps are useful, for basic biology studies.
   - 0.06g may not require free-fall adaptation, or may possibly even aid it.
   - 0.06g may also near the lowest useful level where you can drink from a cup, walk, sit, or roll over in bed without continuing the roll onto the floor.



Possible Design

Advantages of Dumbbell over Donut



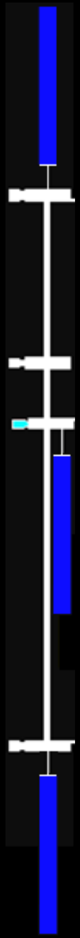
1. A dumbbell layout allows far larger radius & lower Coriolis effects, with lower total mass.

2. An asymmetrical dumbbell provides the 2 most useful partial-gravity levels; one donut cannot do that.

3. One dumbbell module plus a used stage counterweight allow useful early tests and refinements, while a donut is not usable until launch + assembly are complete.

4. A donut of usable size will cost so much that you will have to fly a dumbbell first, to both size the donut & also sell it.

Questions for Early Partial Gravity Bio Research



Near-term manned exploration issues:

1. How much gravity should we use cruising to/from Mars?
2. How much gravity should we use on-station near NEOs?
3. What spin rates and hab designs are best for cruise?
4. What countermeasures will still be needed on Moon or Mars?

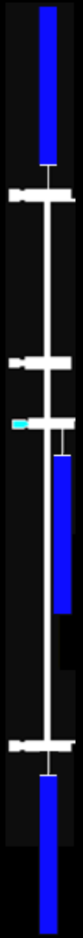
Questions critical for partial-gravity settlements:

5. What are the health impacts of multi-year partial gravity?
6. Can primates (& kids) raised in low gravity return to earth?
7. What crops and ecosystems may be best to use off earth?

Other:

8. What can we learn from ISS's small-sample centrifuges?
9. What conventional wisdom may be wrong about key crops?

What Else Can We Learn from “Moon-Mars in LEO”?



The point is not artificial gravity, but the effects of sustained Moon & Mars gravity. We can’t do this on earth—or cheaply on the moon or Mars.

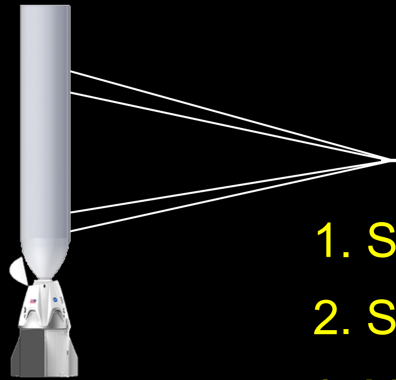
Settlement technologies

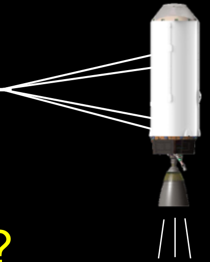
1. If we need >Mars gravity, our future is in spinning settlements!
2. Viability requires food production + *aggressive* recycling.
3. Crops will be just a part of a complex *managed* ecosystem.
4. We don’t know how partial gravity affects crops & ecosystems!

A better understanding of life on earth

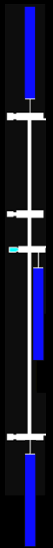
5. Looking at old things in new ways usually reveals new things.
6. What new things can we learn about our most important crops?
7. What small parts of what we think we know are actually wrong?

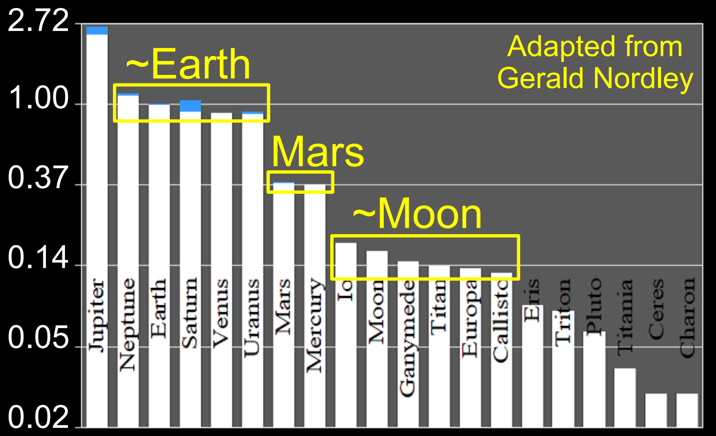
What Are Your Conclusions?





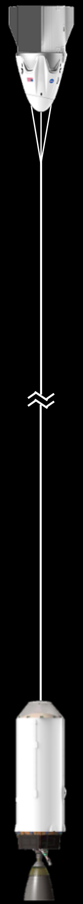
1. Should gravity level clustering affect human space plans?
2. Should we test sustained Moon & Mars gravity in LEO first?
3. Your vacation in space: 0g only, or 0g + 0.06g + Moon + Mars?



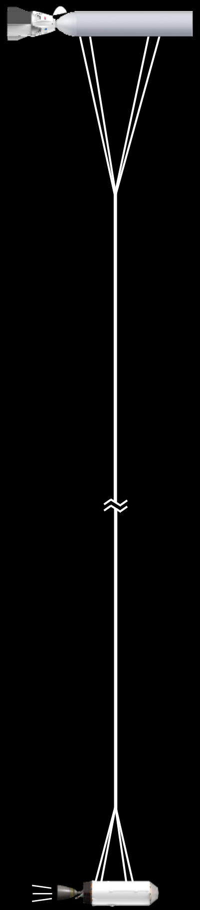


Surface Gravities in Our Solar System

G needs	Our options
If 1/6 g ok	6 moons 2 planets Spin in space
If >1/6 g but 3/8 ok	2 planets Spin in space
If >3/8 g	Spin in space



Backup Slides



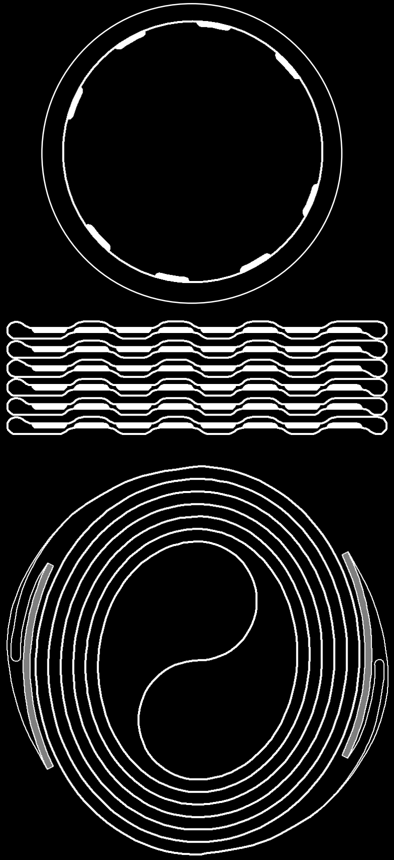
Novel Moon-Mars Item #1: Inflatable Radial Tunnels

Transhab-like inflatable tunnels

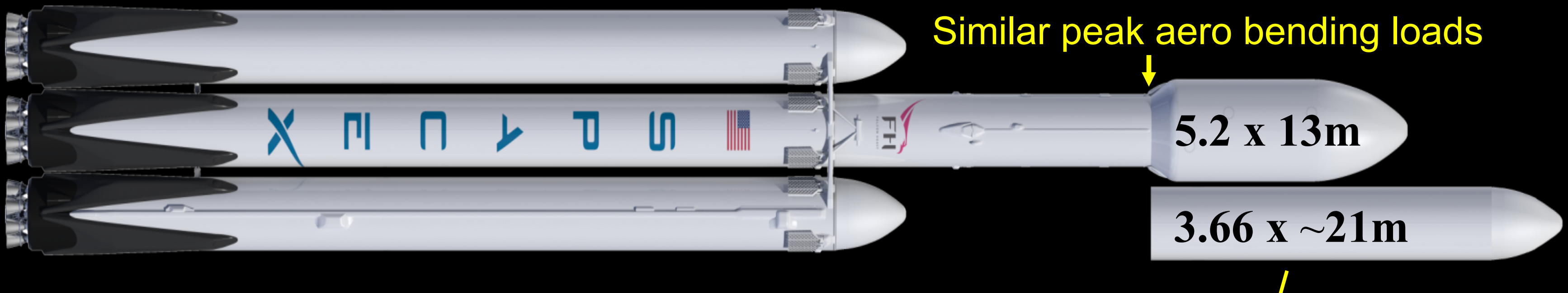
1. Allows shirtsleeve end-to-end travel
2. High-strength fiber in rubbery matrix
3. Standoff film ruptures small impactors
4. Thick straps stop grazing-impact tears
5. Easy to customize, test, and repair
6. Distributed sensors locate damage
7. Translucent version might grow food

Can stow compactly for launch

1. Fold deflated beam in half & roll up
2. 500m tunnel can stow in 3m cylinder
3. Both rigid ends are easily accessible
4. Weak tie-downs allow payout in steps

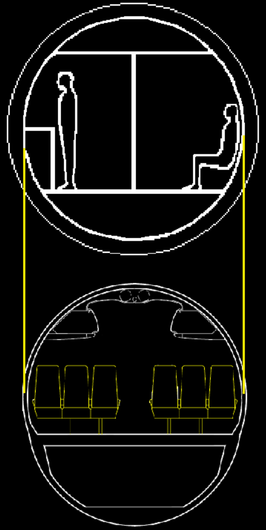


Novel Moon-Mars Item #2: 737-Size Hab Modules

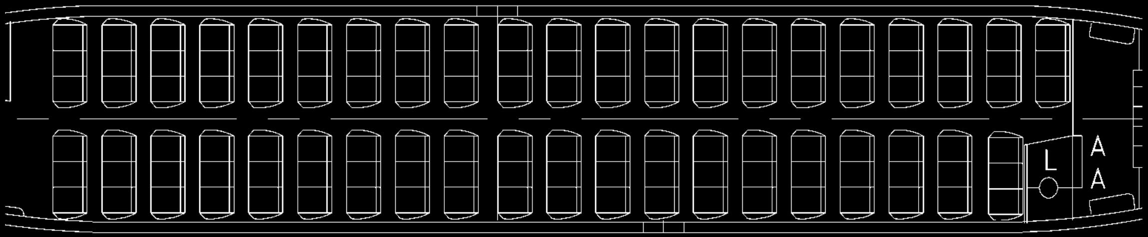


3.66 x 19m
(total payload =
~45 tons w/equip
& supplies)

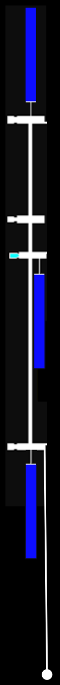
- Build on Falcon tank line; deploy MMOD shield in orbit
- 3.64 x ~19m sealed cabin, with docking port at each end
- 6 modules = 1100m^3, 20% more than ISS module volume



3.54 x 19m
737-600 cabin



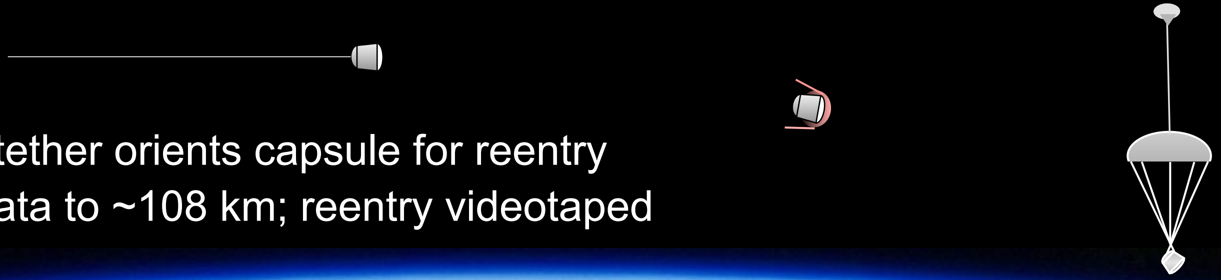
Novel Moon-Mars Item #3: Sample Return Capsules



- Infrequent access from space handicaps use of ISS.
- Bio sample returns might start weekly & grow to daily.

Scenario

1. Stow samples in ~basketball-sized reentry capsule.
2. Pass capsule through small airlock in Mars node.
3. Pay out ~1km of thin tether, and cut loose to reenter.
4. Capture drogue chute in mid-air with small aircraft.



- Trailing tether orients capsule for reentry
- SEDS data to ~108 km; reentry videotaped

Novel Moon-Mars Item #4: Trapeze Captures of Visitors

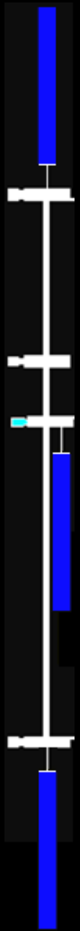
1. Not required, but increases payloads & aids ops.
2. Moon & Mars can capture payloads from MECO.
3. Lets visitors be turned off before getting close.
4. Pair vehicle captures and releases if feasible, or pump water after changes in CM & MOI.

<u>MIT Capture Contest</u>
1990, winning team:
Darryl Pines &
Siegfried Zerweck

<u>Captures *may* be easy using dGPS, cameras, etc.</u>

1. Null out errors during approach, to avoid late panic.
2. Many "hook and loop" interface concepts may work.
3. Dale Stuart did an MIT ScD thesis on this in 1987 & included reacting to sensor & mechanism failures.

Other Key Moon-Mars Support Equipment



Solar arrays

- Hanging arrays with 1-axis tracking reduce structure mass & complexity
- Allow high-power reboost or long tests when sun is far from spin plane

Life support

- Can use ISS type, but using gravity might reduce both problems & costs
- Lots of on-board medical diagnostics, plus frequent bio-sample reentry

Later "space farming" tests, to mature colony concepts?

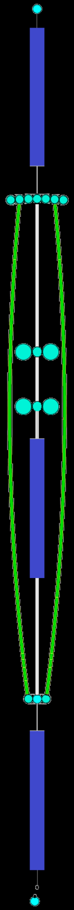
How much "farm tunnel" area is needed to absorb crew CO_2?

Aquaculture can use crop waste to grow fish for added protein.

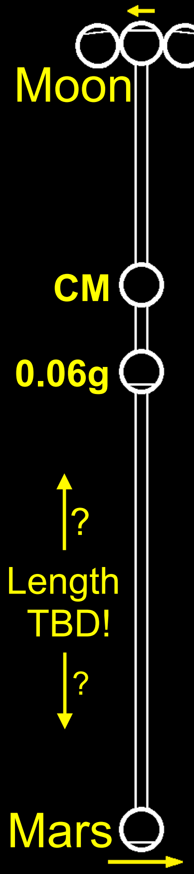
Near-vertical tunnels may ease crop inspection & management.

Some (many?) crops tolerate ~10X more radiation than people.

Could tunnels be used to grow crops outside colony shielding?



How About Testing Other Gravity Levels & Spins?



0.06 gee is the next ~1/e step: Earth - Mars - Moon - 0.06

1. It is easy to add (just another copy of same cabin design).
2. 0.06 gee may be near the lowest level for intuitive actions:
   - Sitting, using a desk, eating, hygiene, even rolling over in bed.
   - Levels like this may be popular w/tourists & crew (unique sports?).

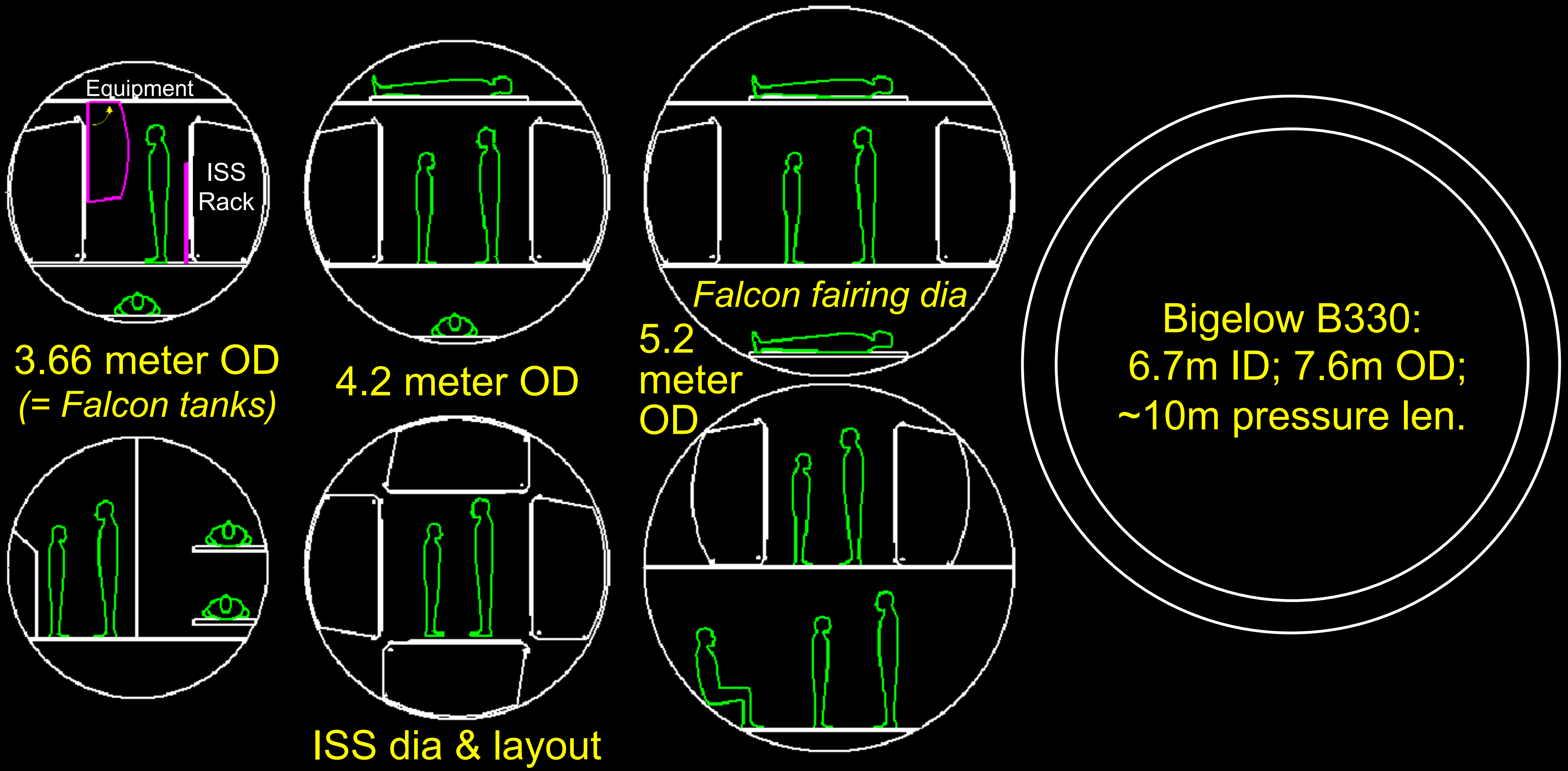
Faster spins with the same facility allow other useful tests

- 1.6X spin gives Earth, plus Mars & Moon at a 2nd spin rate.
- 1.25X spin gives 3 “half step” levels: ~0.6, 0.26, and 0.1 gee.
- *Do faster-spin tests before full outfitting, to limit peak loads.*

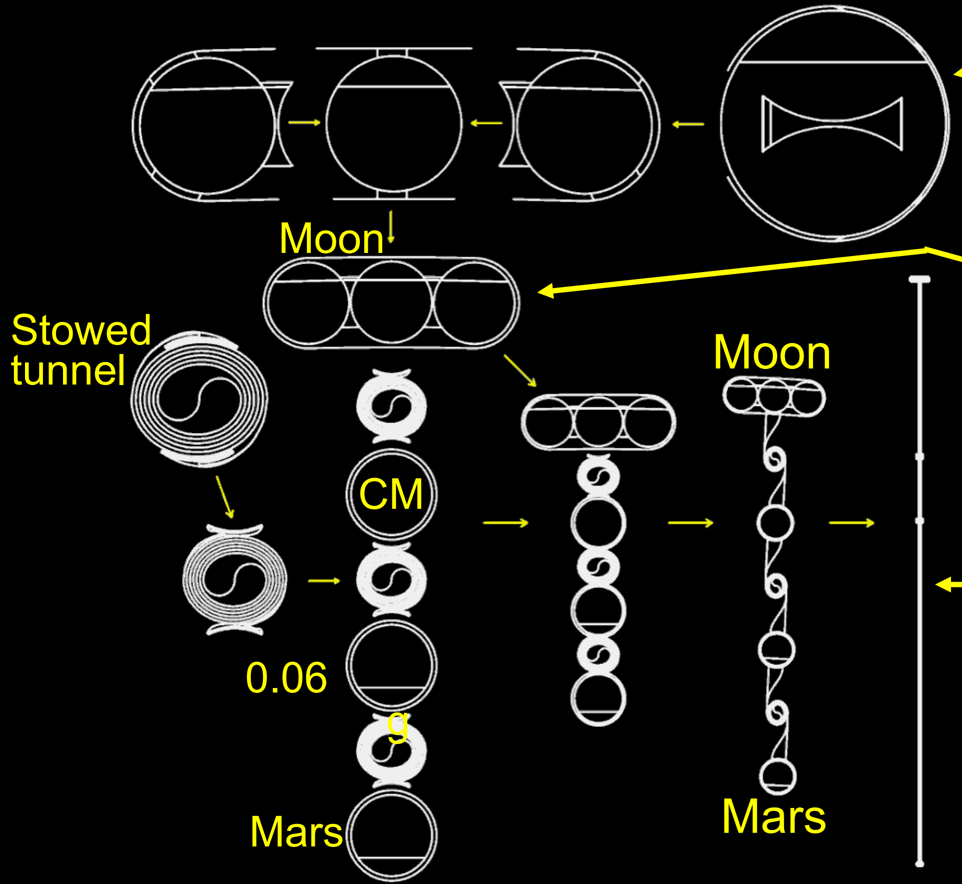
Cycling crew between ends & CM tests “part-time gravity”

- This can test the viability of part-time spin as a countermeasure.
- It can also mimic EVAs to an asteroid near a spinning vehicle.

What Module Diameters & Layouts Should We Use?



Facility Growth from 1 to 3 to 6 Modules

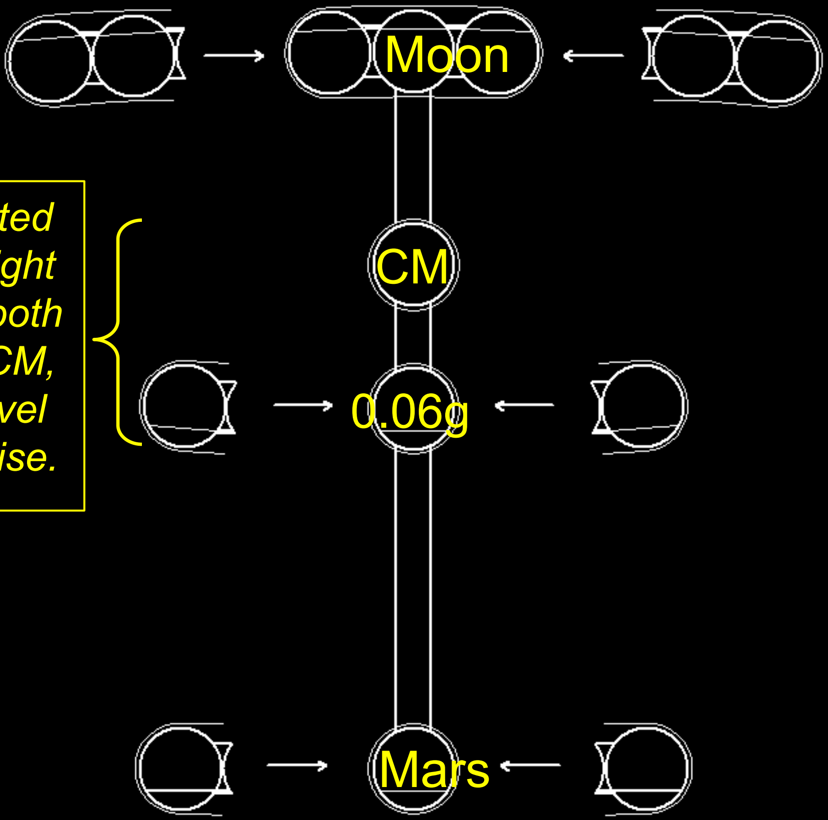


<u>1 module (Moon or Mars)</u>
- Use spent stage as counterweight
- Crew tests spin + walking, etc.
- Sling capsules, and test captures

<u>3 modules (Moon or Mars)</u>
- Release old spent stage & tether
- Attach 2 new modules to old one
- Spin up using a new spent stage

<u>6 modules (Moon & Mars)</u>
- Launch 3 new modules + tunnels
- Use tunnels to join all 6 modules
- Spin up w/thrusters at Mars end
- Weak ties release tunnels in steps

Facility Expansion from 6 to 14 Modules



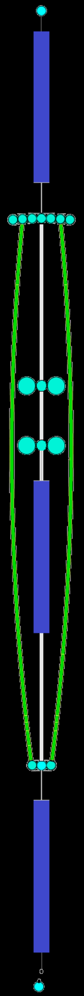
Added inflated modules might be used at both 0.06g and CM, to allow novel low-g exercise.

Facility expansion steps

1. Launch 8 new modules
2. Join the "lunar pairs"
3. Despin (or slow down a lot)
4. Capture & attach modules
5. Spin facility up again
6. Adjust ballast, to balance
7. Finish outfitting new modules

(The above assumes that the tunnels were designed for 14-module loads.)

Growing Food in Long Translucent Tunnels?



Many land-grant colleges already design, build and use spacecraft. Their agriculture aren't involved, but could be!

Why use tunnels to grow food?

1. Large sun-lit areas feasible at low added mass & power.
2. They may be useful in colonies (crop rad. doses ok?).
3. Airflow & rain could aid cabin thermal control.
4. Long vertical tubes should ease farming automation.

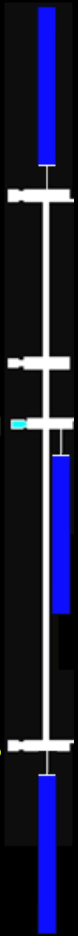
How must overall facility design be modified?

1. Use quartz fiber in silicone for diffuse filtered light.
2. Add tanks and raise fish that eat crop waste mass.

Some key issues need early study:

1. How much crop area is needed to absorb crew CO_2?
2. Can LEDs provide red/far-rad balance for LEO eclipses
3. Is filtered sun in tunnels better than LEDs in modules?
4. Can farm automation experts develop viable designs?

More Analyses of Tunnels



Debris & micrometeoroid protection

1. Thin standoff plasitc film can protect up to ~**1** mm debris
2. Predicted tunnel impacts >1mm/yr: JSC: 100; ESA: 3.
3. Electrical + acoustic sensors locate holes, to plug them
4. Find, track, & dodge >10mm, to limit large exit holes

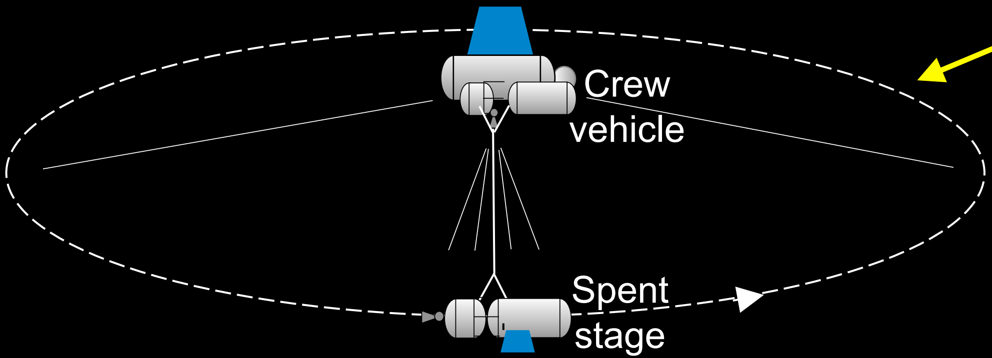
Drag reboost for 1.8 x 480 m tunnel spinning in-plane

1. ISS orbit (~3 ng/m^3); 0.1 N drag: biprop reboost= ~1ton/yr
2. Reboost at 2000 sec I_{sp}, 20kW/N = 163 kg/yr + 2 kW

Crew CO_2 balance during eclipse

1. 20 @ 1.5 kg/day CO_2, 0.6 hr max eclipse= 0.75 kg CO_2.
2. 6 modules + tunnel = 2000 m^3 = +0.15 Torr CO_2 in eclipse

Two Operational Derivatives



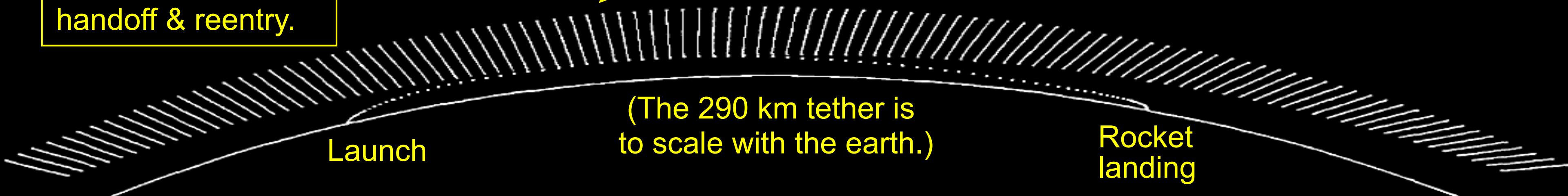
Spinning exploration cruise stage

- Uses spent departure stage as ballast
- Retain stage into Mars orbit & return, with flat spin becoming conical then.
- If tether cut: lose gravity, not mission

High-deltaV spinning LEO tether

- 1.2-3.2 km/sec above ***and*** below V_{LEO}
- Similar trapeze accelerations (0.3-1g)
- Facility must be >50X payload mass; use 2:1 spin/orbit mean rotation ratio.
- ~110 km capture altitude is needed, to allow soft sub-orbital reentries

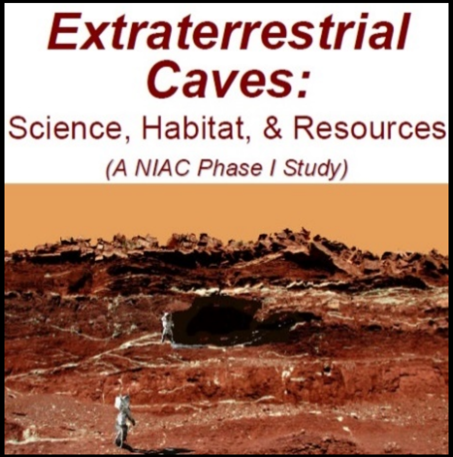
The tether & rocket postions are shown every 10 sec., from launch to payload handoff & reentry.



Where Can We Live, on the Moon or Mars?

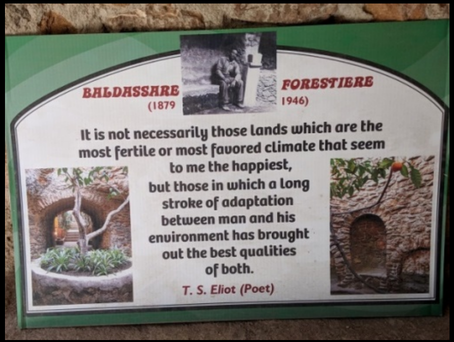
As Dr. Jim Logan says:

- We can visit the Moon & Mars, but we can't live ***on*** them, because of high radiation (solar protons + cosmic rays).
- But we can live ***in*** them, under meters of shielding.

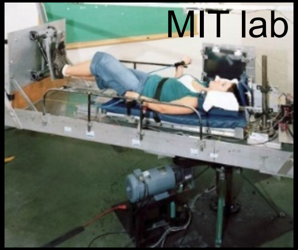


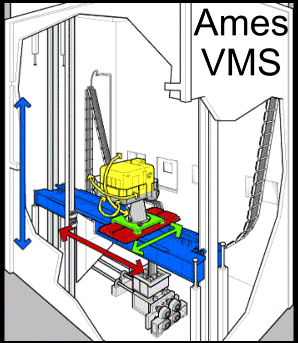
Lava tubes (& bored tunnels!) on Moon & Mars:

- Study Penny Boston's NIAC reports to learn more.
- And to see what living underground could be like, visit www.undergroundgardens.com in Fresno:



We Don't Know What Spin Rates to Use for Artificial Gravity!





Artificial gravity designs with short radii and fast spin will work, if rotating-room results are relevant. But there are big differences:

Coriolis sensations differ greatly

1. In rotating rooms, weight does not change. Walk any direction & you feel a fixed side-force. You adapt.
2. In AG, you may feel 10% heavier if you walk with the spin, and lighter against it. You may stumble, as in elevators (typ. start/stop = 0.05g).

The Vertical Motion Simulator at NASA Ames can cause transient weight changes when you walk.

Effects on the inner ear differ

1. In rotating rooms, spin axis is parallel with gravity. Effects are fixed as you move & turn.
2. In AG, the spin axis, motion, & gravity are all perpendicular. Each turn has a new effect. There is no adaptation time.

Assessing crew queasiness due to inner ear effects may require tether tests similar to Gemini 11.

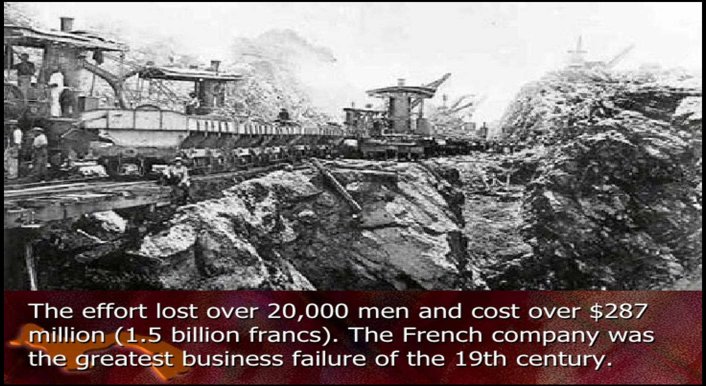
Is the Panama Canal a Useful Settlement Caution?

A recap of the failed French effort

1. Built and ran a good hospital—but did not screen out mosquitos!
2. Suez accessed France's colonies. What did Panama access?
3. Several % of budget was spent on bribes to legislators & editors.
4. Funding was private; company went bankrupt after ~40% done.

Why might this be relevant?

- **Is sustained low gravity the next "malaria & yellow fever"?**



A great book on Panama canal:

"The Path Between the Seas"

Bibliography

The Panama Canal: The Path Between the Seas, by David McCullough. French effort = cautionary tale?

Gravity and rotation effects

M. Roach, Packing for Mars: The Curious Science of Life in the Void, W.W. Norton & Co, 2010. A fun read and good overview.

G. Clement & A. Bukley, eds, Artificial Gravity, Microcosm & Springer, 2007. Goes into detail on health effects of microgravity.

G. Nordley, Surface Gravity and Interstellar Settlement (version 3.0 September 2016), www.gdnordley.com/_files/Gravity.pdf

J. Vernikos, The G-Connection: Harness Gravity and Reverse Aging, iUniverse, 2004.

T.W. Hall, "The Architecture of Artificial Gravity: Archetypes and Transformations of Terrestrial Design," in Space Manufacturing 9, Space Studies Institute, 1993; available along with many other papers on artificial gravity at www.artificial-gravity.com/

A. Graybiel et al, "Observations on Human Subjects Living in a "Slow Rotation Room" for Periods of Two Days," Arch. of Neurology, 3, 55-73, 1960.

F. Guedry et al, "Human Performance During Two Weeks in a Room Rotating at Three RPM," NASA & US Nav. Sch. of Av. Med. Joint Rep. 1962.

Concepts for artificial gravity facilities

Al Globus, http://space.alglobus.net/papers/Near-Term-Policy-and-Research-Priorities-to-Enable-the-First-Space-Settlement.pdf

D.D. Lang and R.K. Nolting, "Operations with Tethered Space Vehicles," NASA SP-138, 1967; at https://ntrs.nasa.gov/archive/-nasa/casi.ntrs.nasa.gov/19680005472.pdf. Also see tether video at 6:40 & 10:40 at www.youtube.com/watch?v=j6EWMjgRTdg.

K. Sorensen, "A Tether-Based Variable-Gravity Research Facility Concept," 53rd JANNAF Prop. Meeting, 2005.

B.K. Joosten, "Preliminary Assessment of Artificial Gravity Impacts to Deep-Space Vehicle Design," JSC-63743, NASA, 2007; available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070023306.pdf.

J. Carroll, "Design Concepts for a Manned Artificial Gravity Research Facility," paper IAC-10-D1.1.4, Prague, Sept-Oct 2010.

Basis of this presentation. Has far more on facility concepts. See www.artificial-gravity.com/.

Food production and other recycling concepts

K. Kalbacher de Marquez and E. Marquez-Gonzalez. "Aquaponics: An Option for In-situ Production of Mission Consumables", 9th Symposium on Space Resource Utilization," AIAA 2016-0720, AIAA SciTech, San Diego, 2016.

N. Katayamaa et al, Space Agriculture Task Force, "Entomophagy: a key to space agriculture," in Adv. in Space Research, 41:5, 701-705, 2008.

H. Jones, "Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?" ICES-2017-85, available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170007268.pdf