National Aeronautics and Space Administration

Artificial Gravity Research

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Background and Motivation

- **Humans experience multiple, significant negative effects in the space environment, believed to primarily stem from microgravity and radiation exposure**
  - Current countermeasures reduce the negative effects but do not solve the problems
- **NASA is currently considering “fast” Mars missions relative to previous conjunction class missions in order to address these crew health issues**
  - Results in a 4-8x increase in gross mass of the Mars Transport Vehicle
  - This solution does not address the root cause of the issue
- **This approach warrants reconsideration of a slow, shielded, artificial gravity mission**
  - May be achievable in a safer manner for less mass and reduced cost
  - This solution begins to address the challenges of living off-planet for the long haul

Current understanding suggests any habitat that does not fully address the microgravity and radiation exposure issues of deep space will be insufficient to sustain long duration human presence beyond Earth.

Artificial gravity and radiation shielding are currently theorized to be the most effective solutions

Negative Impacts of Microgravity

Alice Elberfeld

Establishing the Problem

- Currently any time spent in space results in an exposure to microgravity.
- The human body responds to this environment, often in ways that are unfavorable to overall health.

- Examples of negative effects of microgravity:

- Muscle deconditioning
- Bone decalcification
- Visual Impairment Intracranial Pressure Syndrome (VIIP)
- Fluid shift

Muscle Deconditioning

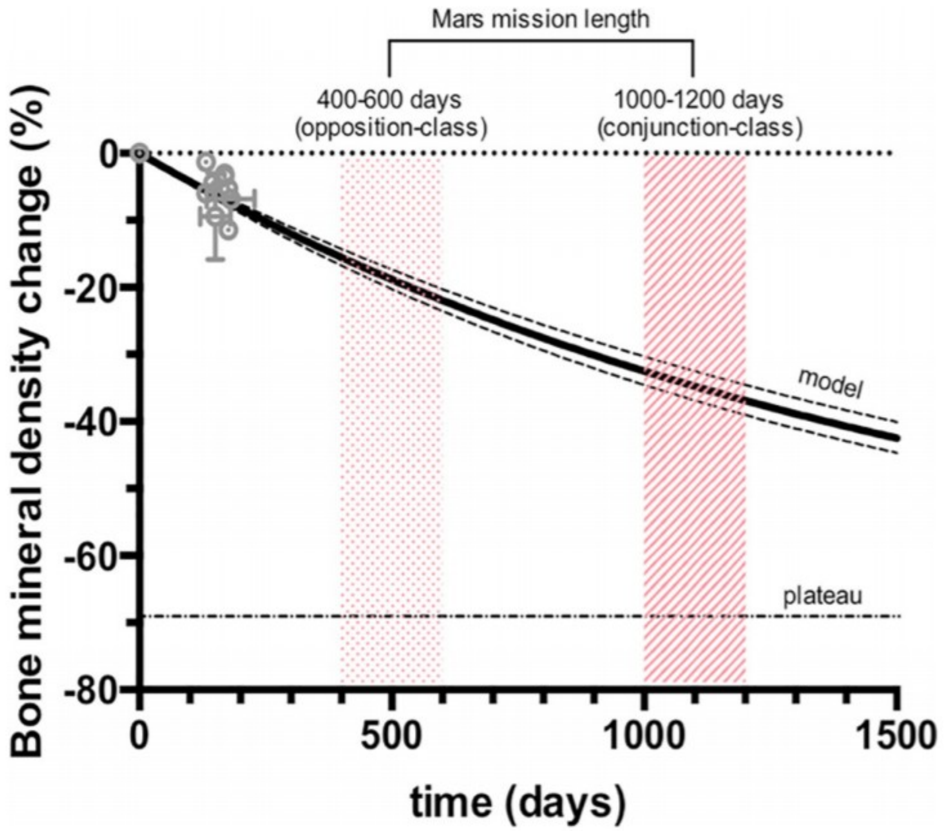
- **Health effects:** Weakness, increased recovery time upon return to Earth.
- The disuse of muscles while in microgravity results in atrophy in a matter of days without proper countermeasures.
- **Countermeasures:** Resistive Exercise for up to 2.5 hrs a day
- Increased focus on endurance training exercise shows potential to better counteract the negative metabolic effects.
- **Artificial gravity as a potential countermeasure:** By creating forces similar to Earth, Muscle will be used to stand and move around. Effectively replicating conditions on Earth.
- Astronauts still face some significant muscle loss during extended stays on the ISS, **long-duration missions** are at higher risk for greater levels of muscle loss due to increased time spent in microgravity.

Credit: NASA

Bone Decalcification

- **Health effects:** Osteopenia, osteoporosis, increased susceptibility for bone fractures, increased levels of calcium in the blood.
- Due to the lack of loading on weightbearing bones, bones start to breakdown.
- **Countermeasures:** Resistive exercise can be used to counteract some of the loss but is only partially effective.
- **Artificial gravity as a potential countermeasure:** "Downward" forces will provide the loading on bones necessary for normal health. Gravity gradients may effect the amount of force on different bones in the body.
- **Long duration / Mars missions** face serious risk of astronauts developing osteopenia or osteoporosis, greatly increasing their risk of bone factures.

<u>Bone mineral density change over time without countermeasures</u>



Bone mineral density change at the femoral neck of astronauts versus duration of spaceflight. (Predictive Model)

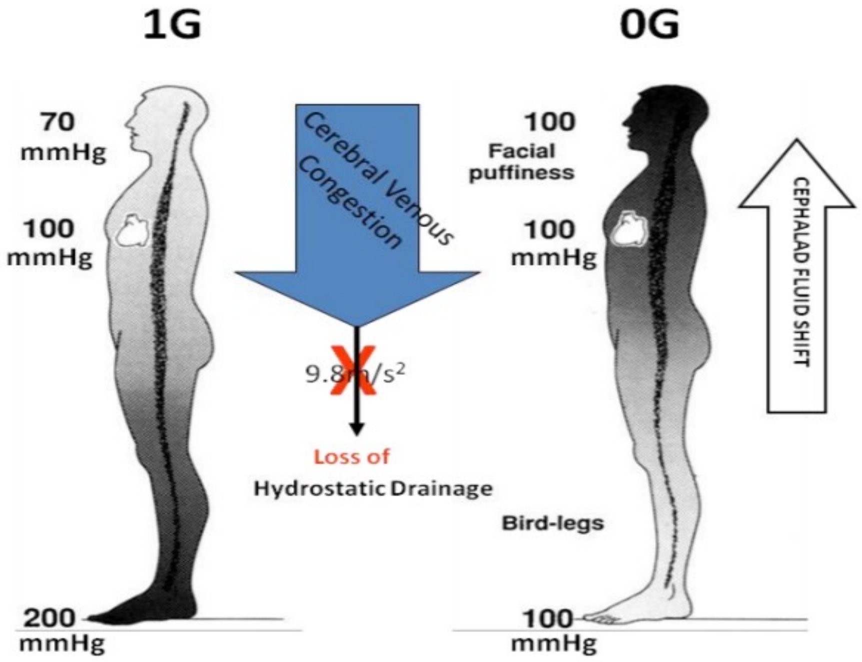
- Grey dots represent experimental data obtained from previous missions before ARED implementation in 2009.

Source: Axpe E, *A human Mission to Mars: Predicting the bone mineral density loss of astronauts*

Fluid Shift

- **Health effects:** “Bird-legs” and puffy face, increased intracranial pressure, VIIP, nasal congestion, headaches.
- As the body is no longer working against gravitational forces, fluid starts to shift away from the lower extremities and into the upper body.
- **Countermeasures:** There are currently no countermeasures to effectively control fluid shift
- Possible countermeasures: Small human centrifuges and lower body negative pressure suits are current proposals for counteracting fluid shift.
- **Artificial gravity as a potential countermeasure:** By providing forces similar to those experienced on Earth, fluids will return to the lower body.
- **Long duration / Mars missions** are high risk for complications, extended exposure to increased intracranial pressure may result in permanent vision changes.

<u>Fluid shift visualization</u>

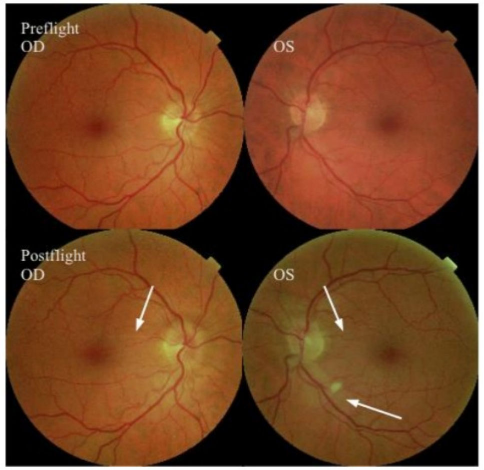


Source: Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure (Pg. 72)

Visual Impairment Intracranial Pressure Syndrome (VIIP)

- **Health Effects:** Changes in vision, blurry vision, spots, decreased peripherals, swelling of the optic nerve
- VIIP encompasses any vision changes experienced during spaceflight due to increased pressure on the ocular cavity. It theorized to be caused by the increased intracranial pressure that results from fluid shift in microgravity. 80% of ISS astronauts have report negative effects to their vision during their stay.
- **Countermeasures:** There are currently no countermeasures. Adjustable glasses are used to provide relief for vision loss and maintain astronauts ability to focus. Any method that effectively controls fluid shift in microgravity could potentially provide relief for VIIP.
- **Artificial gravity as a potential countermeasure:** Fluid shift management by artificial gravity will relieve the increased pressure on the upper body and the optical nerve.
- **Long duration / Mars missions** are uncharted territory. We still don't know the full effects of VIIP or what the long duration missions may mean for astronauts vision.

Fundus examination of visual changes from long-duration spaceflight. Fundoscopic images showing, choroidal folds (white arrows) in the papillomacular bundle area in the right eye and left eye and a cotton-wool spot (bottom arrow) at the inferior arcade in the left eye. Both optic discs show grade 1 disc edema.



Source: Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure (Pg. 11)

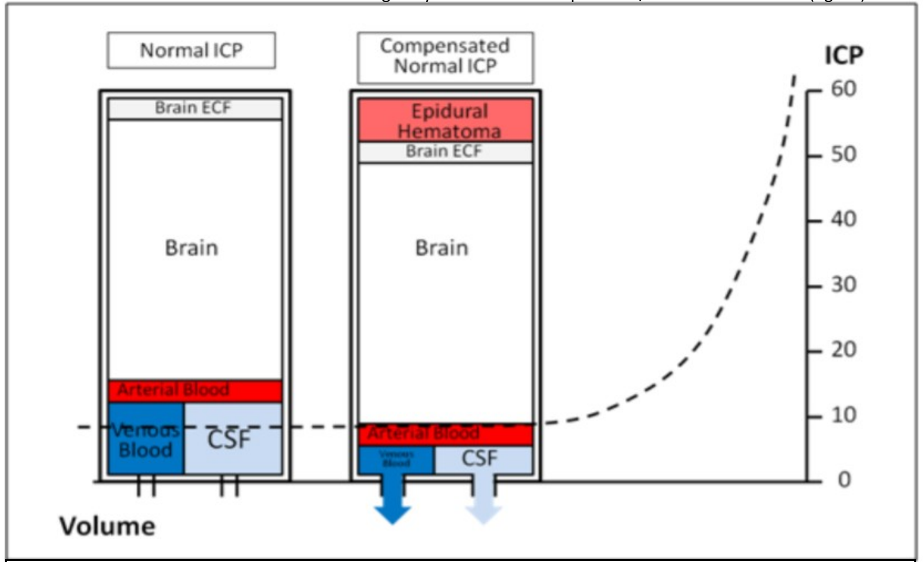


Diagram showing the small buffering capacity that allows for increases in intracranial volume.

Source: Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure (Pg. 71)

Why AG may be a solution

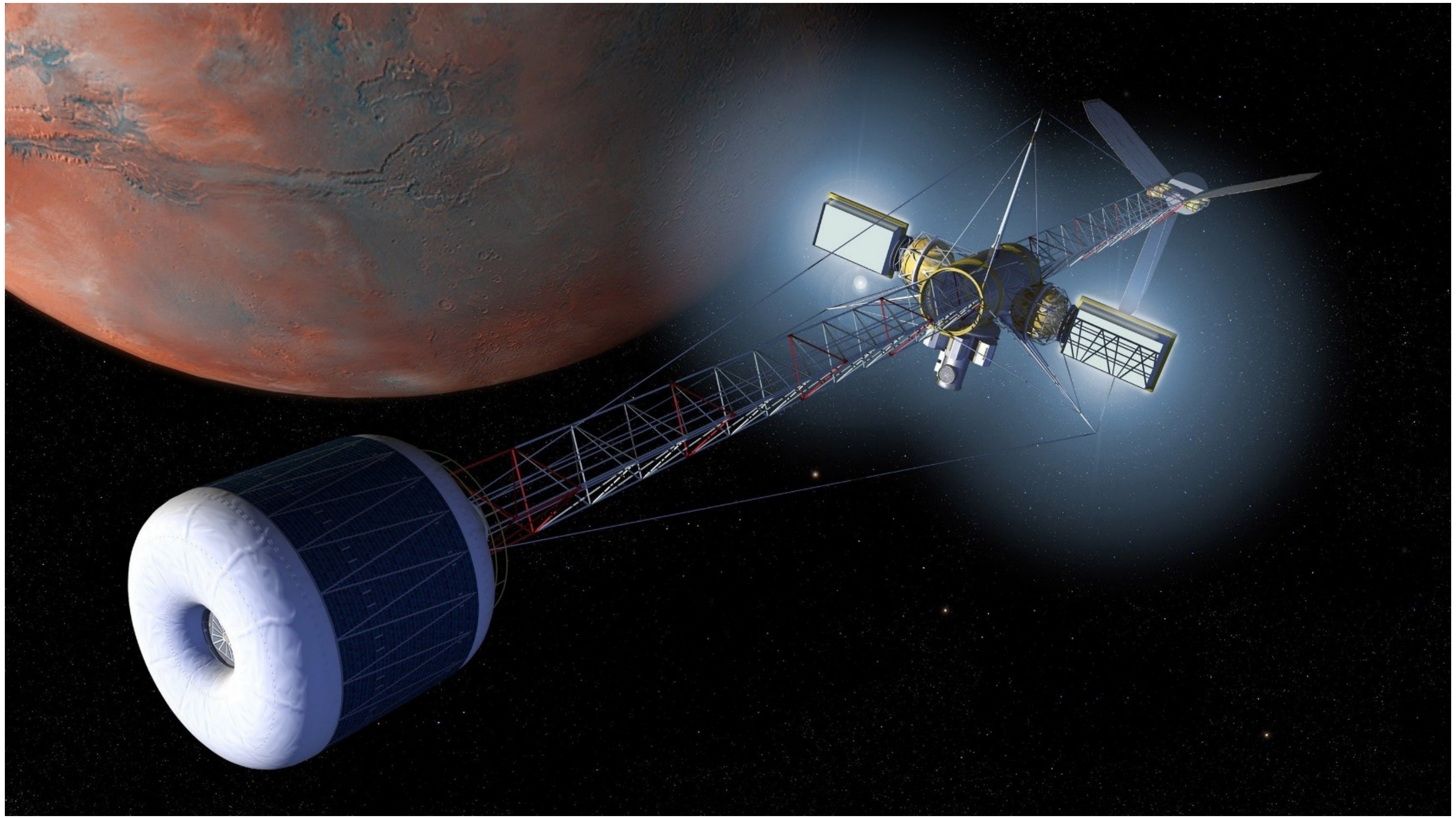
- By providing similar forces to the ones we feel on earth there is potential to entirely mitigate many of the negative effects currently experienced in microgravity
- Bones and muscles will be subjected to full or partial 1g forces consistently, decreasing the need for exercise as a countermeasure
- Fluid will be directed back towards the lower body relieving intracranial pressure
- Recovery time will be less of an issue for transferring to a body with substantial gravity
- Reaction times should be immediate and muscles will be ready to resist the gravity of the Earth, Moon, or Mars

Physics, Challenges, and Constraints

Cody Beard

Identify Major Challenges and Constraints

- Relationship of radius and rotational rate
- Coriolis Effect and force
- Gravity Gradient
- Other physical challenges and limitations (Cross-Coupled Angular Acceleration)



Source: NASA

Relationship between the radius and the rotational rate

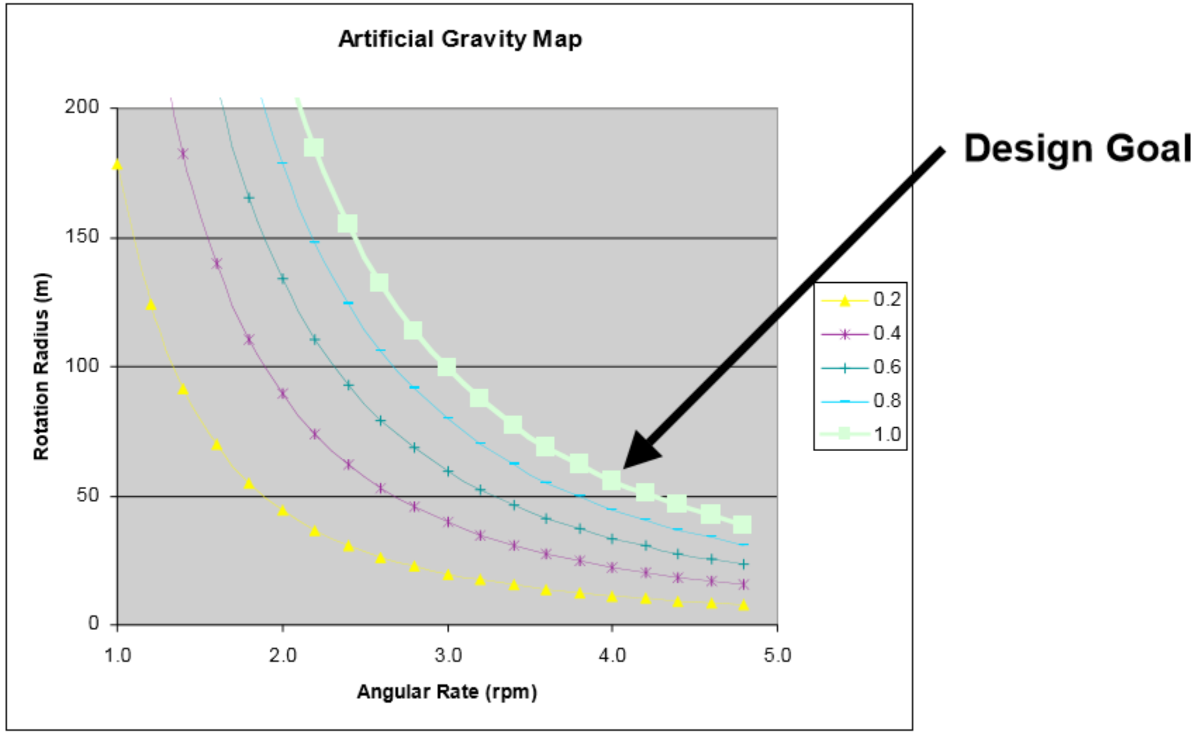
$$a_c = \frac{v^2}{r} = w_c{}^2 r = \frac{4\pi^2 r}{T^2}$$

$$\frac{2\pi}{60} rad/sec = 1\, rpm$$

w_c = rotational speed in radian/sec

- v = velocity in m/s
- r = radius of the circle
- T = time period (time it takes to complete one rotation)

a_c = centripetal acceleration



Source: NASA

- The relationship between the radius and rotational rate is quadratic. The rate of rotational speed is squared compares to the rate of the radius.

Coriolis Effect

- Happens when an object or subject moving in a rotating structure

- Equation: $F_c = -2m\,(\omega_c \times v)$

- ω_c = The rotational rate
- m = The mass of the object or subject
- v = linear velocity of the object or subject

- For example, if you and your friend are playing catch in a rotating merry go round, if you pass the ball to your friend the ball appears to be curving against the rotation of the merry go round. However, to the observer from the outside of the merry go round, the ball appears to move linearly.

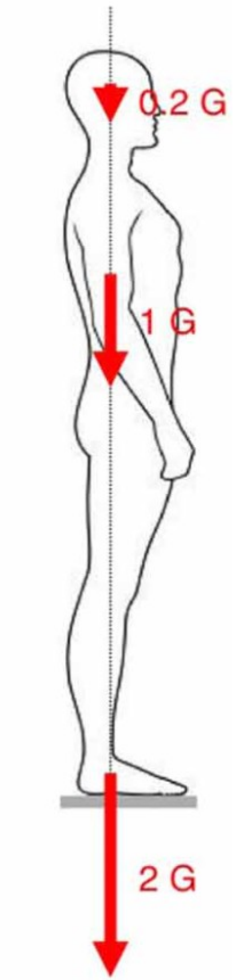
Gravity Gradient

- Ratio of Head acceleration to Feet acceleration
  - Equation:

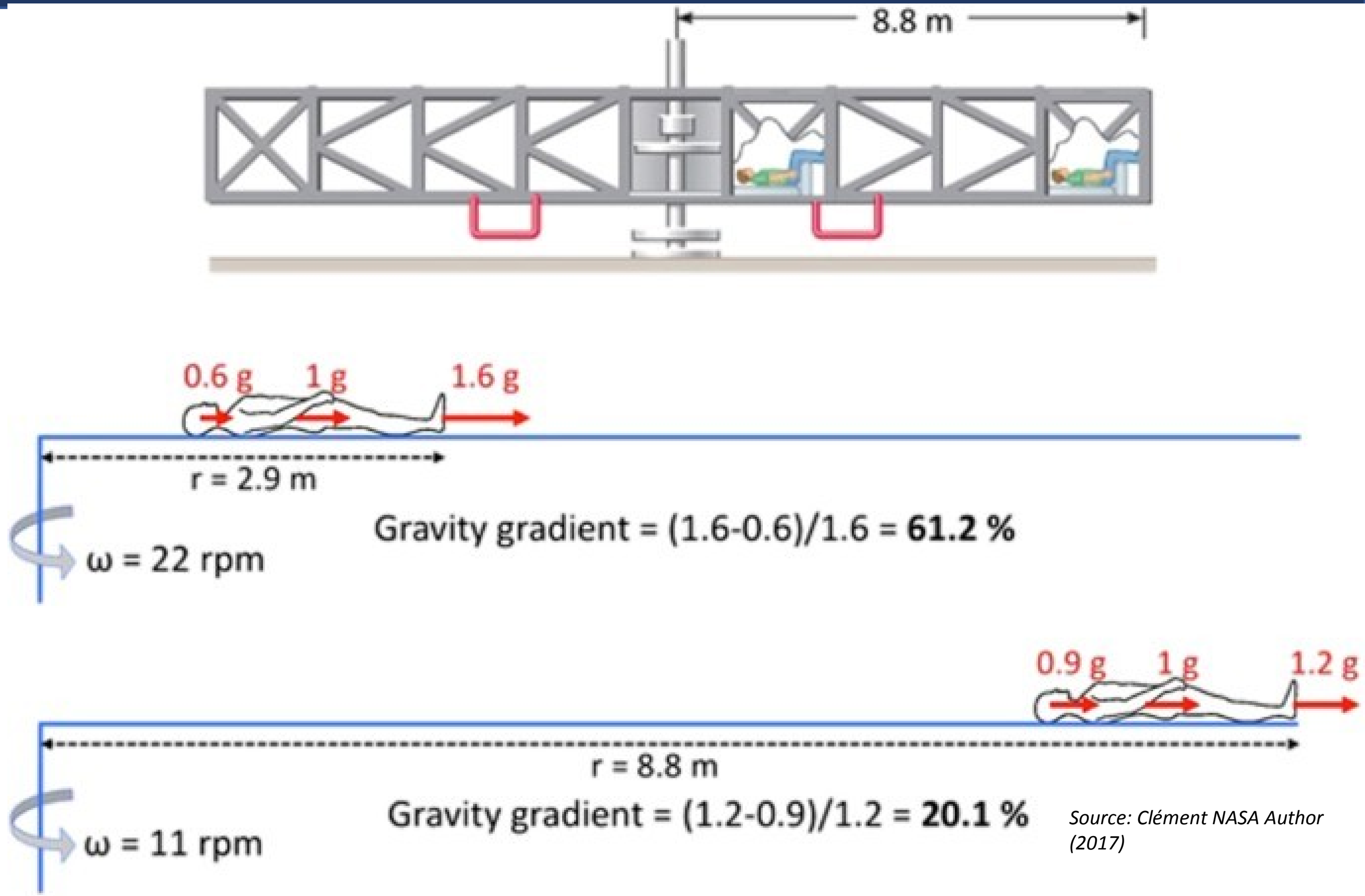
$$A_{head}/A_{foot} = \omega_c^{2} r \frac{(r-h)}{\omega_c^{2} r} = \frac{r-h}{r}$$

- Hydrostatic pressure - The pressure exerted by a fluid at a given point on the body, due to the force of gravity
  - Equation:

$$p = d / 2\,(h^2 - r^2)\,\omega_c^2 r$$



Source: Clément NASA Author (2015)

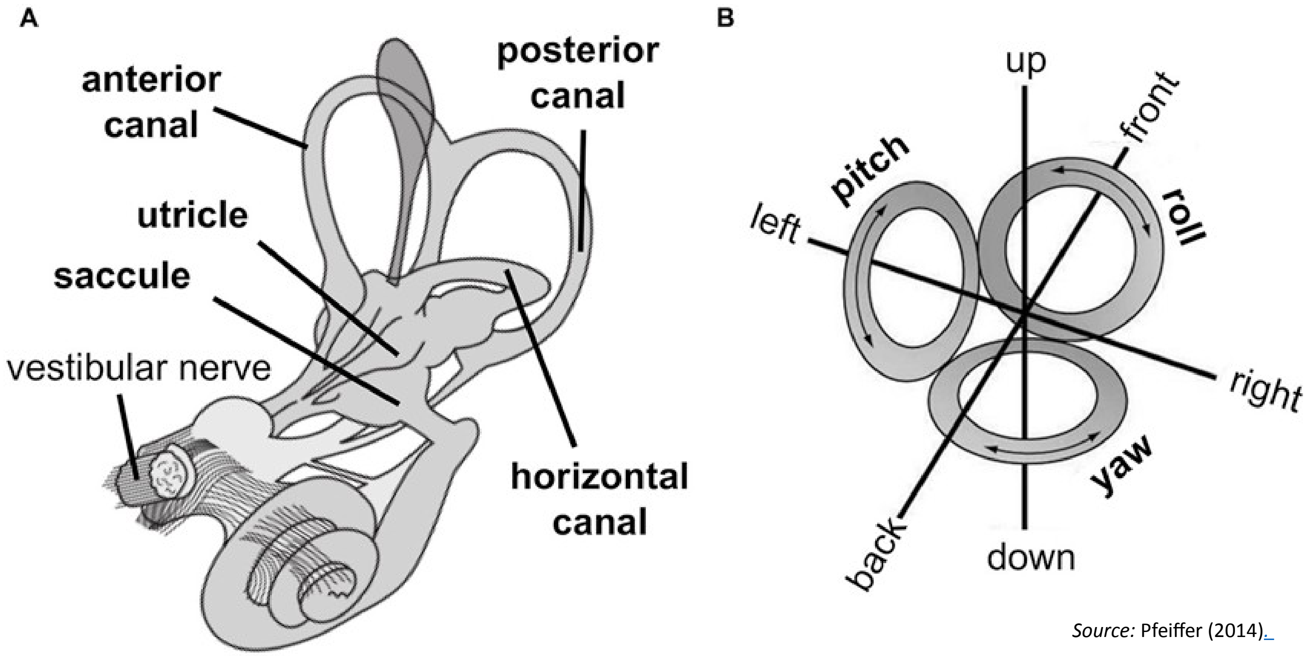


Source: Clément NASA Author (2017)

Cross-Coupled Angular Acceleration or Vestibular Coriolis

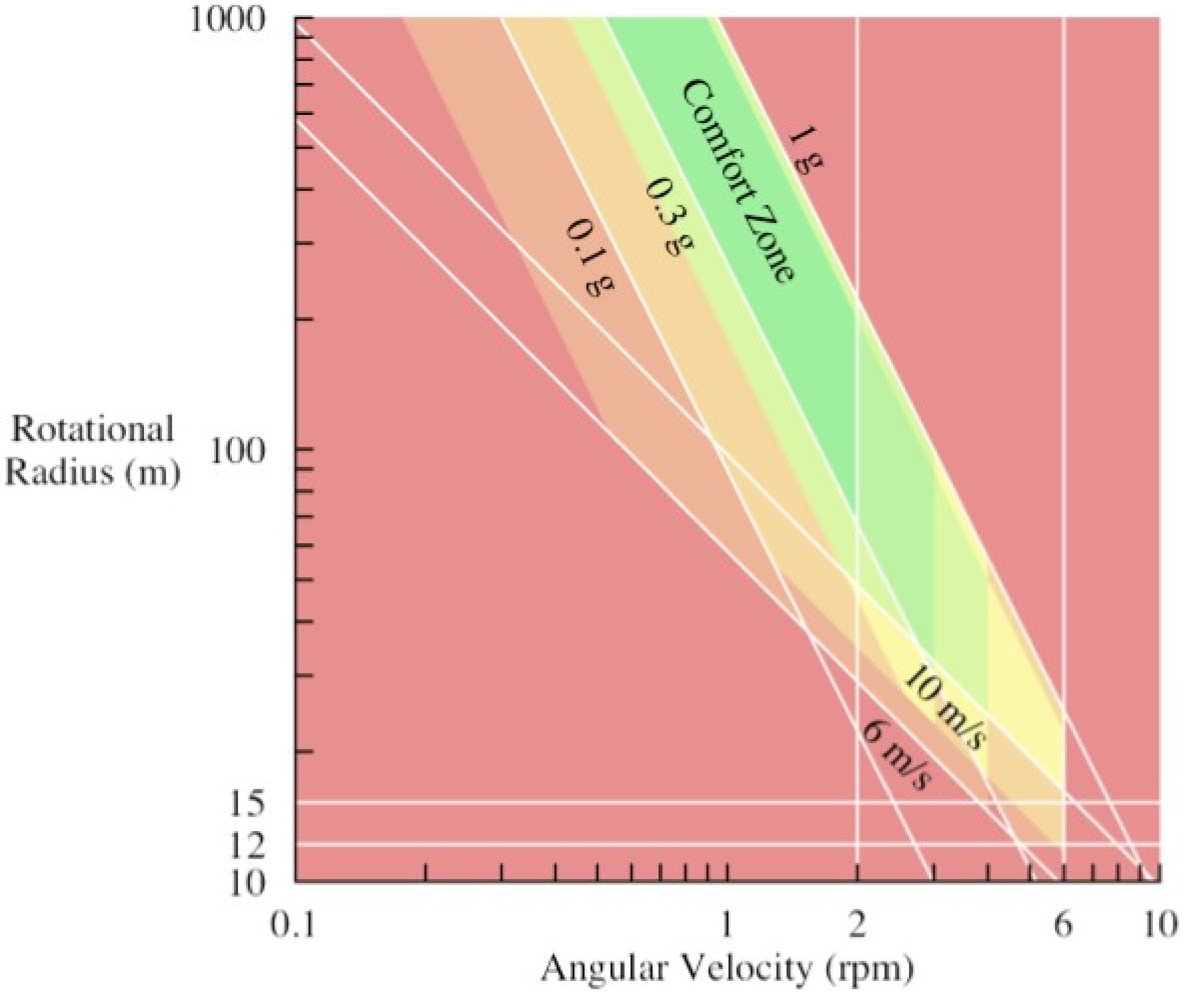
- This occurs when a subject rotates his or her head about a plane axis that's not aligned with the rotation of the habitat.

- Equation: $CCAC = \omega_c \times \omega_h$
- ω_c = rotational speed of the centrifuge
- ω_h = rotational speed of the subject's head



Source: Pfeiffer (2014).

Comfort Zone



Source: Hall, T. W [6]

Author	Target $\frac{A}{9.81}$ (g)	Min. V (m/s)	Min. R (m)	Max. $\frac{30\Omega}{\pi}$ (rpm)
Hill & Schnitzer [1962]	**1.00**	23.4	55.9	**4.0**
Gilruth [1969]	**0.90**	14.0	22.4	**6.0**
Gilruth "optimum" [1969]	**0.90**	42.1	201.2	**2.0**
Gordon & Gervais [1969]	**1.00**	15.6	24.8	**6.0**
Stone [1973]	**1.00**	14.7	22.1	**6.4**
Cramer [1985]	**1.00**	31.2	99.4	**3.0**

Source: Hall, T. W [6]

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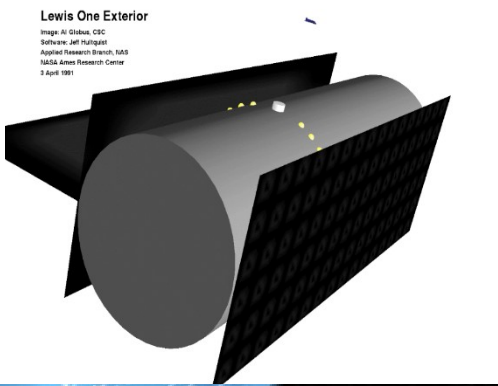
Past Artificial Gravity Concepts

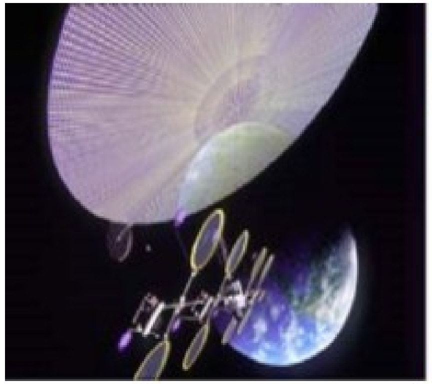
Beth Westfall

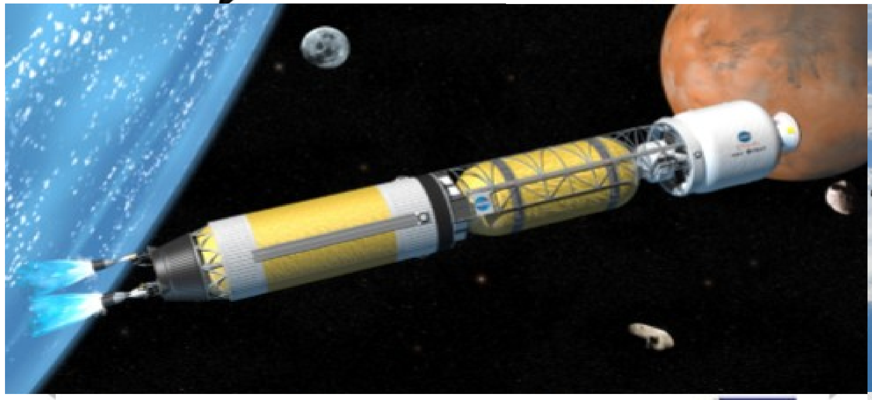
Build a Better Solution

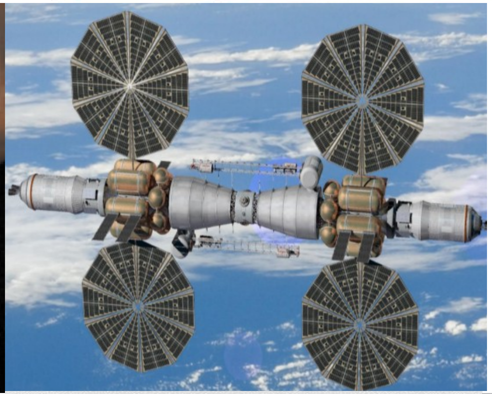
- AG concepts:
- Stanford Torus
- Bernal Sphere
- O’Neill Cylinder
- Lewis One
- Bimodal Engine
- ARMSTRong Model
- Kalpana One
- SLS LOX Tank
- Suspension Cables
- Tether Module
- Linear Sled

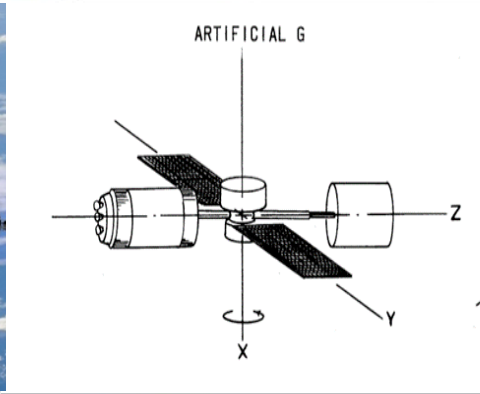
Image citations are referenced throughout the presentation

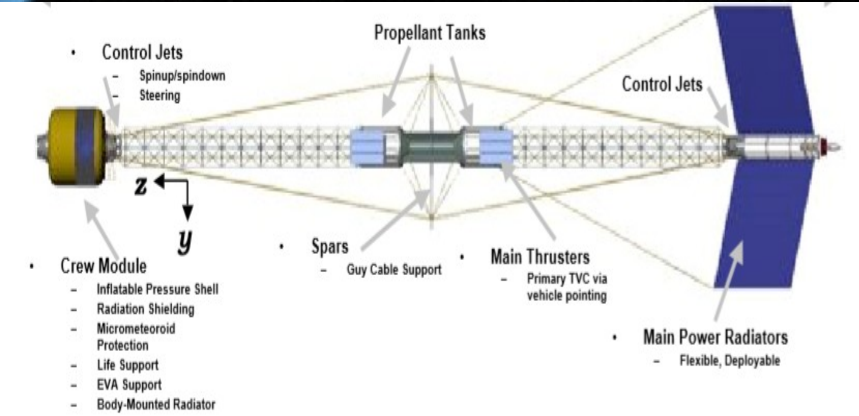


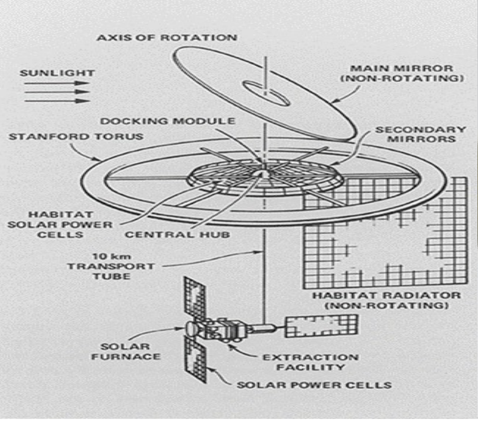


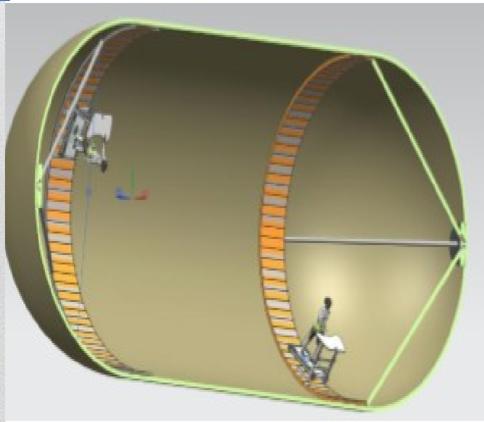








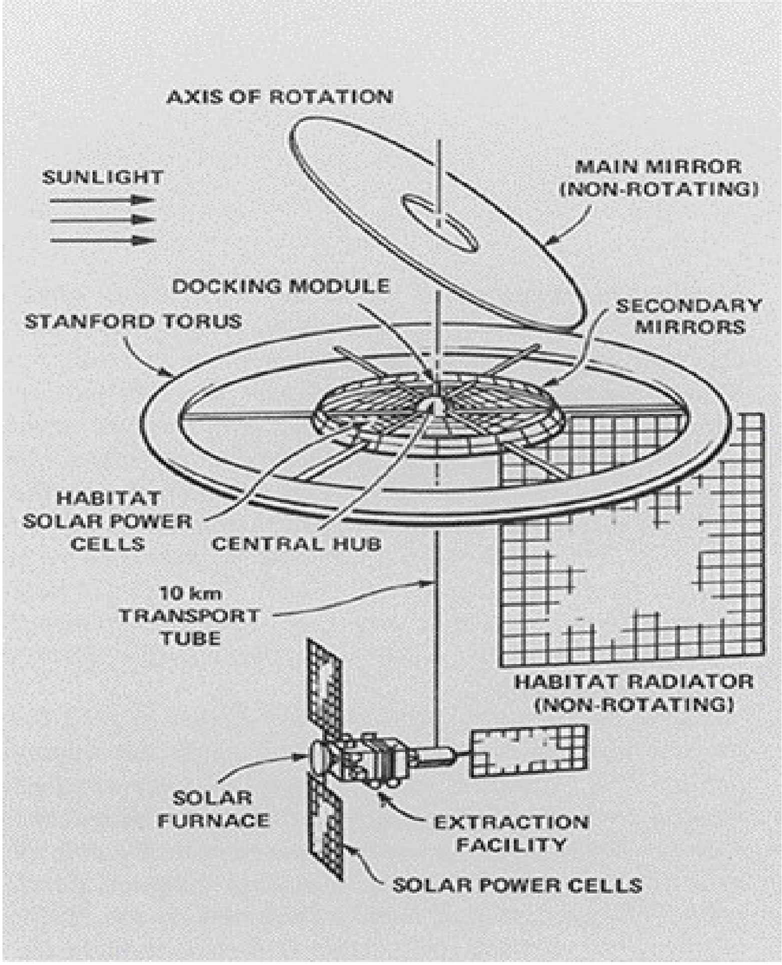




Stanford Torus

- This concept has a great energy protocols that allow numerous features and allows for a larger radius which would allow for more supplies and room to move around.
- This concept has notable challenges such as the potential giant mirror, which isn't absolutely necessary. It would also need to be scaled down in size as it was designed for a whole space colony.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This design shows promise although it is not the best design.



Citation: (Martelaro 2017)

Bernal Sphere

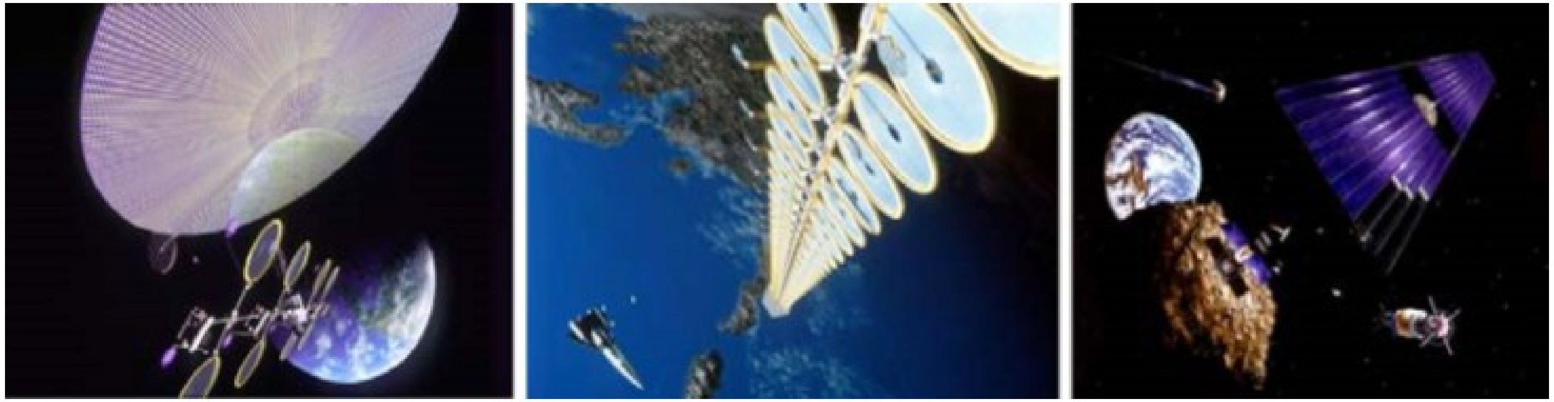
- This concept includes several different gravity levels within the space craft as well as a spacious design.
- This concept is another design concept built in mind of having a space colony, however if it is scaled back it does have some good features.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This design shows promise although it is not the best design.

O’Neill Cylinder

- This concept has benefits such as the ample space inside of the craft as well as a good setup for artificial gravity implementation.
- This concept has challenges such as the severe Coriolis effect and how expensive it would be to build a solid steel cylinder.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This design shows promise although it is not the best design.



Citation: (Curreri & Detweiler 2011)

Kalpana One

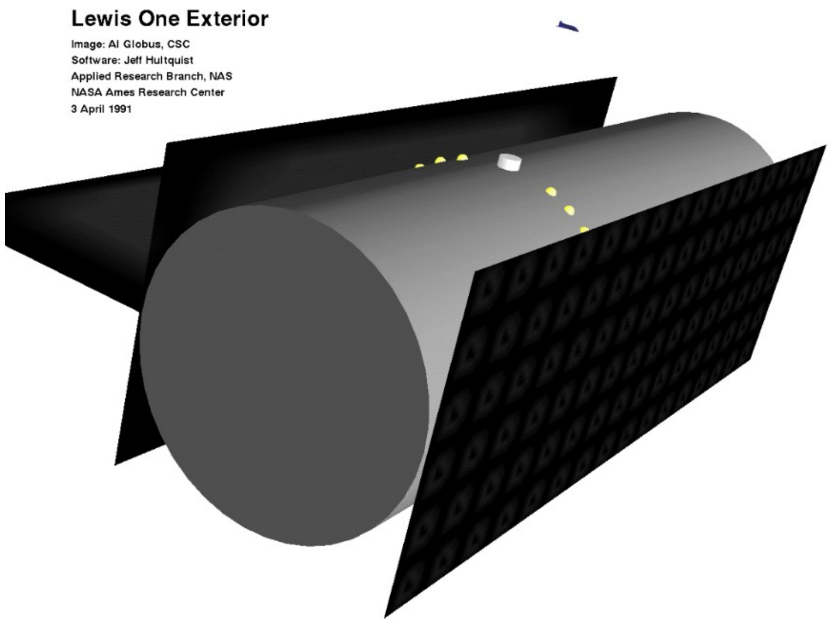
- This features a similar design to that of the O'Neill cylinder as it is essentially just a short and fat version of the tall and skinny O'Neill cylinder. This design has more wobble control and natural light advantages than its counterparts as it its rotational axis is that of the Solar System's north-south axis.
- This is another design concept that was made with the idea of a whole space colony so we would need to drastically downsize this model for it to be considerable.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This design shows promise although it is not the best design.

Lewis One

- This concept features a range of gravitational forces throughout, ranging from the Moon to Earth in small increments. This would be critically important as it would be very helpful in the adjustment the crew would face.
- The flaw is the incredibly large design as it was designed in the late nineteen hundred's when scientists were looking at artificial gravity in order to form a space colony.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This design shows promise although it is not the best design.

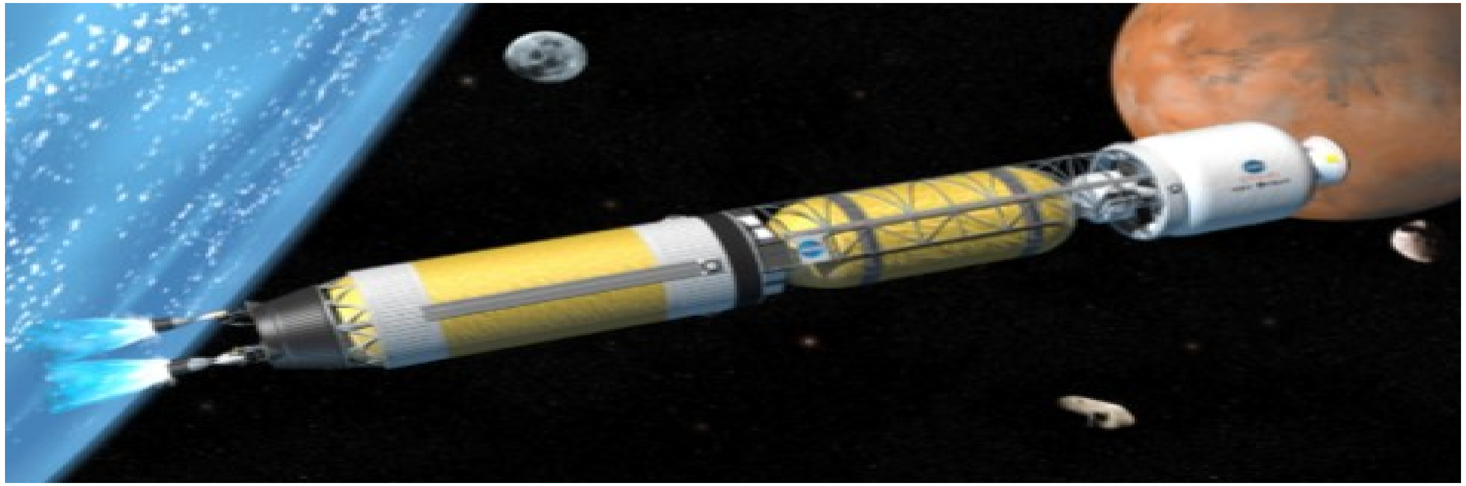


Citation: NASA

Bimodal Engine – Rotating NTP

•This provides high thrust propulsion and continuous twenty-four seven electrical power. It would be rotated about its center of mass and perpendicular to the flight vector would create the centrifugal force and the artificial gravity environment. This design is naturally equipped to be an artificial gravity environment.
•These are high thrust engines which would require a lot of energy or fuel which would be expensive.

•It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
•This concept shows great promise as it has a natural design and few downfalls.



Citation: (Borowski, McCurdy, & Packard 2014)

ARMSTRong Model-Artificial Gravity Rotating Modular Space Transport

•This design has a main hub and two deployable wings. This design is more cost efficient than others because of the flexible wings that deploy.
•If the wings are inflatable or made of a material that is flexible that does add the challenge of the stability of them once they are deployed in space. The temperature of the wings is also of concern as the material will not support moderate temperatures.

•It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
•This design shows promise but needs to have the physics worked on.

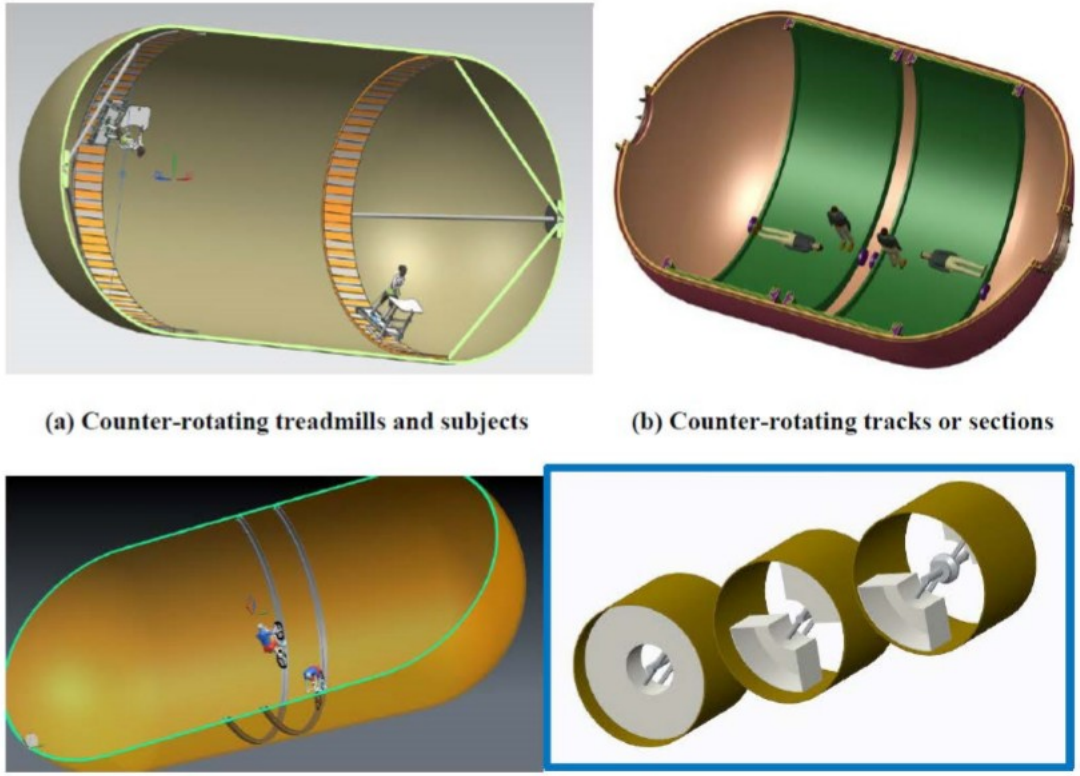
SLS LOX Tank

•This design concept features a tank that would rotate as opposed to rotating the whole spacecraft. This tank could be inflatable with a steel shell or just made from metal entirely. It could have tracks on the inside.

• It will have the Coriolis effect and it will be a challenge to deal with since we are shortening the radius the spin rate will have to increase and that could lead to negative health effects.

•It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.

•This shows a good deal of promise as it simplifies some the rotational variables but will lead to complications.



(a) Counter-rotating treadmills and subjects

(b) Counter-rotating tracks or sections

(c) Cycle ergometer with counter-rotation

d) Enclosed track or gondolas

Citation:(Zipay 2019)

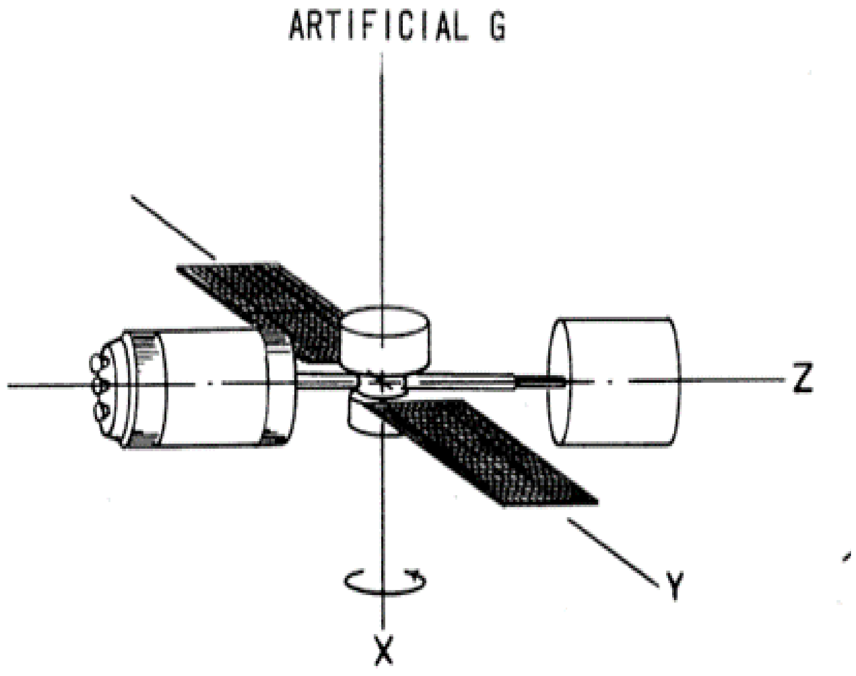
Tether Module

•This design cuts down cost by using tethers and will allow for the radius to be rather large which will help in rpm calculations. The docking port would act as a center for low gravity operations and as a counterweight for the crew module.

•There would need to be a mechanism to spin up and spin down the facility quickly which has yet to be developed. Another challenge would be tracking inertial targets form a rotating facility of this design. The tethers are also not as sturdy as it would be preferred.

•It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.

•This design shows a great deal of promise but needs to have some physics worked out.

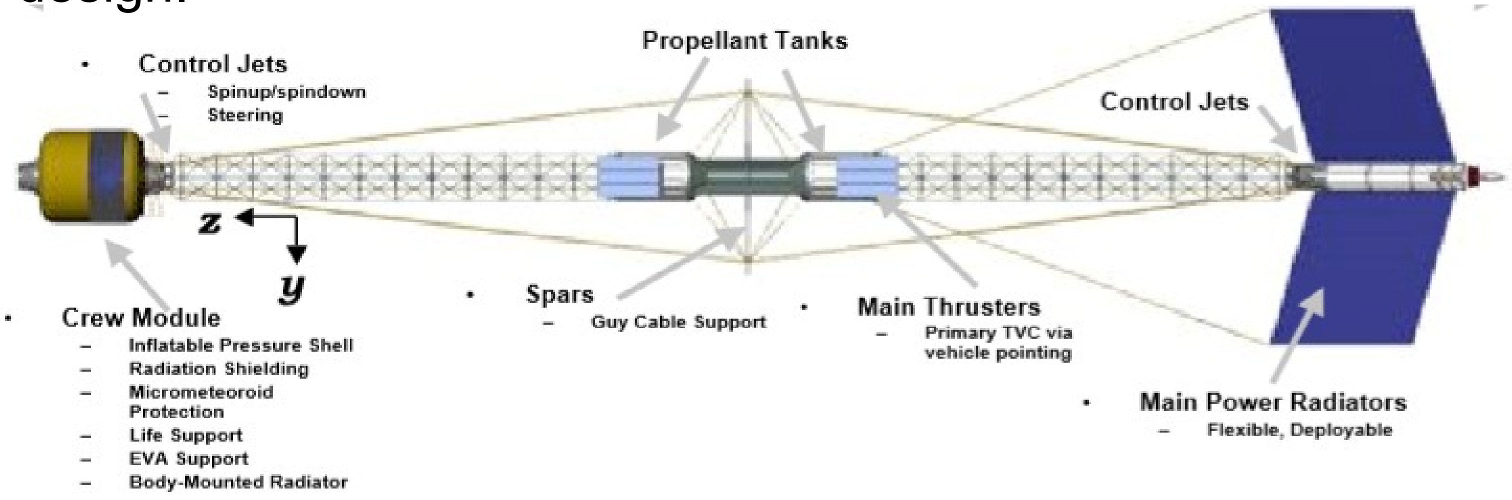


Citation: (Sorensen 2005)

Suspension Cables

- This design features suspension cables(tension cables) which are a sturdier way to cut cost down but increase the radius; this will allow for the rotation rate to be kept at a conservative number.
- Challenges include CG offsets in habitat and power modules causing stability concerns; there are a lot of moving parts so there is a lot of error sources.

- It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.
- This concept shows great promise and once the minor issues get worked out, this could be the best design.



Citation: (Joosten 2002)

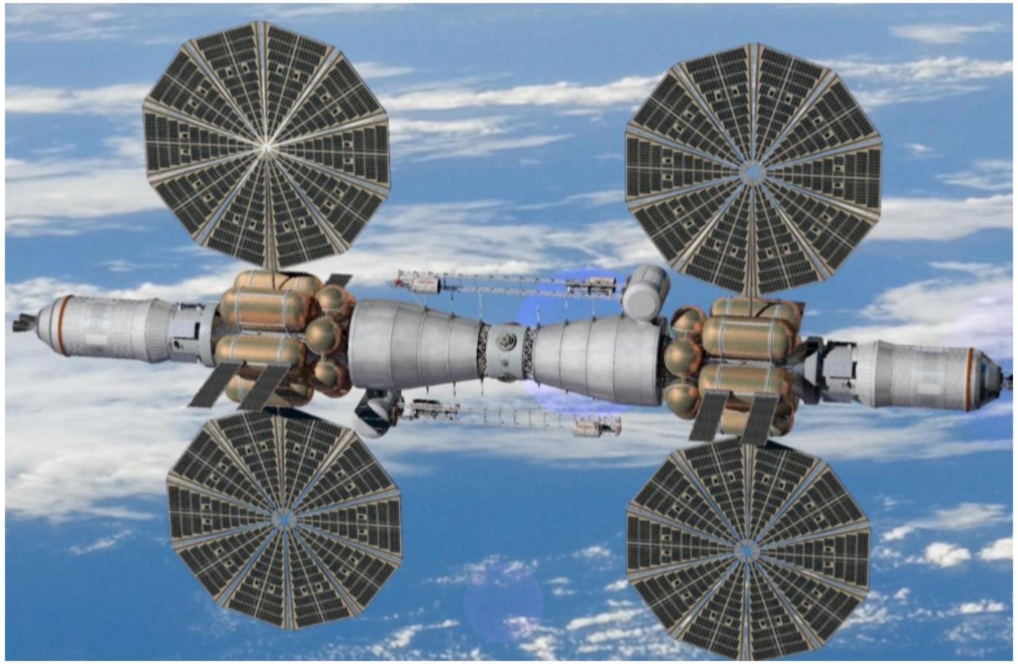
Linear Sled

•This design would create artificial gravity by linear acceleration. It would achieve this by attaching a track to a space craft and then accelerating an astronaut forward and then flipping them and decelerating them(feet above head) on a sled on the track. This limits the Coriolis effect as they are not rotating the entire space craft.

•The length of the track and acceleration rate is similar ratio debate to that of radius and spin rate; there is simply not enough research done to be able to give a concrete number.

•It would need to be adapted for near-term implication because it allows for a spacious living environment and creates an artificial gravity environment.

•This design needs to be furthered researched before it is seriously considered.



Citation: (Gruber 2018)

Where we go from here…

- This work is a first step and provides a foundation for future work
  - Negative health effect caused by microgravity and current countermeasures
  - Artificial gravity as a countermeasure
  - Physics of artificial gravity spacecraft
  - Artificial gravity spacecraft concepts
  - Artificial gravity community of practice

Artificial Gravity on SMAB SharePoint

- Near term goal: Develop an alternative to "going fast" for human missions in the inner solar system
  - Continue developing body of knowledge through research
  - Discussions with AG advocates across the agency, focus on barriers to acceptance
  - Develop concept for AG habitat and associated campaign for comparison

- Long term goal: Ability for humans to safely live in space for decades

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