Design Study on Short Radius Centrifuge as Countermeasure against Prolonged Exposure to Weightlessness

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Recent publications presents short arm centrifugation (SAC) as a promising and potential countermeasure system against undesired effects from prolonged exposure to weightlessness, such as deconditioning of cardiovascular, bone, muscular functions and otolith-ocular reflexes [1]. Furthermore, the use of SAC show decreasing illusory tilt and motion sickness of the crew by adaptations to the artificial gravity (AG) environment [2]. SAC has previously been ignored as a useful countermeasure against prolonged exposure to weightlessness since most literature, the past 40 years, were based on 24 hour comfort living criteria's. Based on the potentials of SAC, this paper will present a design study on a short radius centrifugation (SRC) countermeasure system based on; an integration into a 963 days crewed Mars mission, artificial gravity adaptation parameters, new launching diameters of 7.5 m based on the NASA Exploration Systems Architecture Study (ESAS) [3], 6 crew members placed supine on a rotating platform(s) for sleeping or pure countermeasure. Furthermore, the paper will discuss, but not conclude, useful g-loads based on previous literature to perform necessary countermeasure, crew head and body movements performed in the SRC environment, duty-cycle possibilities, engineering parameters for maintaining attitude-control and different design configurations of the rotating community system to maintain a healthy social life on board a crewed mission to Mars.

Keywords: Short arm centrifuge, countermeasure, artificial gravity, design study

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I. Introduction

The human presence in space is one of the biggest technological achievements of our civilization. But great achievements do not come without a prize. Space is a hostile environment not suitable for humans and going there is dangerous. Radiation, vacuum, extreme temperatures, micro meteorites and changes in gravitational forces are just few of the factors making human space mission a difficult and dangerous task. Furthermore, launching limits in sizes and masses for the artificial space environmental in combination with weightlessness complicates our daily lives as well as change the way we perform our tasks.

This paper will present a design study on a short radius centrifugation system for 6 astronauts as part of a 963 days mission to Mars. The paper will go through some history and definitions of countermeasure possibilities and artificial gravity (AG) as well as proposed AG duty cycles and amplitudes. The final design will be presented as a variety of options in order to satisfy future decisions of countermeasure-needs and to trade off between the engineering complexities and ethical values within these options.

II. Humans in space

The most significant transition in going from Earth to Space is weightlessness. Weightlessness can be created by a constant free fall around Earth, know as micro-gravity (µG), or experienced by traveling beyond the major gravitational forces from planetary bodies, known as zero gravity (0g).

Weightlessness

Weightlessness is one of the main reasons we go to space [4, 5] because it provides a unique scientific environment for research and development. The elimination of gravity from our experiments helps us getting many answers in all disciplines of science that are normally affected by Earths gravity. The exposure of weightlessness to astronauts is typically of short to medium durations. US space shuttle missions last 7-9 days and visits to the International Space Station (ISS) last 3-6 month.

Exposure to weightlessness has many undesirable effects on humans. These effects are roughly divided in two categories: performance-effects and medical-effects. Performance-effect is the effect of weightlessness on our routines, such as showering, sitting or meal preparation. Medical-effect is the psychological and physiological effect of weightlessness, such as loss of bone mass due to elimination of mechanical stresses on body tissues or sensory deprivation due to loss of general orientation.

In many cases there is interaction between both categories. A medical-effect, such as motion sickness (MS), can have a serious impact on performance skills as well as poor performance can impact the mood of crew members. The effects are mostly characterized as negative; however, particularly regarding performance there are many positive aspects of being in a 0g environment where as the medical-effects are mostly negative. Table 1 lists a brief overview of some of the most typical medical effect on a crew member from exposure to weightlessness.

> *"The unique feature of weightlessness is that weightlessness gives you the possibility to create any gravity you like, from hypo- to hyper gravity. This is unique, from a scientific point of view. Of course, it is also fun".*
>
> Dr. Chiaki Mukai, Japanese astronaut (STS-65 Columbia and STS-95 Discovery)
> During a private discussion about microgravity at the International Space University 2005

Effect	Description
Body fluid shift	Weightlessness creates a body fluid balance shift towards the head.
Fluid loss	Fluid balance shift results in fluid reduction by urination due to overall fluid increase interpretation by the brain.
Red blood cell loss	As much as 0.5 liter of red blood cells is suspected to be lost.
Muscle damage	Absence of constant gravity pull reduces muscle mass.
Bone damage	Absence of constant gravity pull reduces bone mass by app. 1%pr. month.
Immune system change	The body becomes easier accessible to virus attacks and becomes more sensitive to radiation.
Drug impact change	Drugs are absorbed differently in the body due to fluid shift.
Spatial disorientation	The brain gets spatially confused when orientation by the ocular system is not confirmed by the vestibular system. Loss of natural up- and downwards orientation also result in disorientation.
Space motion sickness	Sensory conflict results in discomfort, blushing, vomiting, nausea, sweating, headache, loss of concentration. Last 1-3 days. [6]
Olfaction and taste degradation	Nasal congestion might cause decreased olfaction and taste capabilities. [7]
Weight loss	Loss of bone mass, muscle mass and fluid results in weight loss.
Spine extension	Absence of gravity pull extends the spinal column by several inches. [7]
Facial distortion	Body fluid shift towards the head results in puffy face. Emotional expressions become hard to read.
Zero gravity body posture	The body is at rest in a position with slightly bended arms, knees and slightly downwards facing head.

Table 1. Some medical effects of exposure to weightlessness

Countermeasure

Counter-measuring weightlessness meaning counteracting or mitigating the effects of weightlessness. This can be done using different methods such as exercise, medical treatment or pressure suits, all with varying duty cycles e.g. 1 hour per day with varying amplitudes. The combination of these parameters depends on the mission scenario. A short mission to the Moon has very different countermeasure requirement than a 3 year crewed mission to Mars.

A countermeasure option such as fluid intake, salt loads and use of anti-g suits before a weakened body, exposed to long periods of weightlessness, is descended to Earth, Moon or Mars [8] can be considered a short duration countermeasure in comparisons to daily exercise for many months on the ISS. Even though the daily exercise is only performed a couple of hours a day on board the ISS the complete countermeasure objective is as long as the mission it self and would be considered long durational. A medical countermeasure against 1-3 days space motion sickness would be considered a short duration countermeasure.

Some effects, due to prolonged weightlessness, have a critical- or irreversible point (IP) where rehabilitation is no longer possible. If exposed to weightlessness beyond the IP it will not be possible to regain that particular body function. IP's are difficult to determine and varies from particular body functions and amongst crew members. The most accurate way to determine IP is by experience, but then it might be too late. We know by flight records that more than 12 months exposure to microgravity still gives astronauts or cosmonauts a change to completely recuperate. [9]. Furthermore, a crewed mission to

Mars, will require transitions to different planetary bodies and exposure to different g-loads, which is why the countermeasure also must help to prepare successful g-load transition without posing danger to crew members. As a conclusion: the main goals of countermeasure should be maintaining a healthy body, postponing the IP for later total recovery and to endure safe g-load change.

III. Artificial gravity

The slow degradation of the human body, when exposed to weightlessness, is a great concern which is why countermeasure by exercise is a part of the everyday schedule of every astronaut [10]. However, many of these traditional countermeasures appear to be insufficient for prolonged exposure to weightlessness [11, 12].

Countermeasure against weightlessness is theoretically best done by creating gravity in space. But, creating a perfect gravity environment in space, as we know it from Earth, is practical and economical impossible due to large diameter requirements. Also, creating an earth like gravity-environment does not make it Earth-like [4]. Nevertheless, artificial gravity still poses as a potential option, which will be discussed and examined further in this paper,

History

The idea of artificial gravity in space dates back to 1923 in Hermann Oberth publication "Die Rakete zu den Planetenraumen"[*] were Oberth suggested artificial gravity by spinning a habitat. In 1928 rocket engineer Hermann Potocnik[†] (1892-1929), suggests in his book "Das Problem der Befahrung des Weltraums"[‡] the use of rotating space stations as a means of obtaining artificial gravity. His space station Der Wohnrad (living-wheel) had a diameter of 50 meters, rotating to create a habitable gravity area in the outer ring (See Figure 1) [13] .
The work by Hermann Potocnik has beyond doubt been a great inspiration to Wernher von Braun (1912-1977). Von Brauns works on artificial gravity started with a space station in the same diameter as Potocnik's, accommodating a crew of 80 people (See Figure 2) [14]. This station was further developed and presented by von Braun in 1952 (See Figure 3) and later used in Stanley Kubricks science fiction feature film "2001" (See Figure 4).

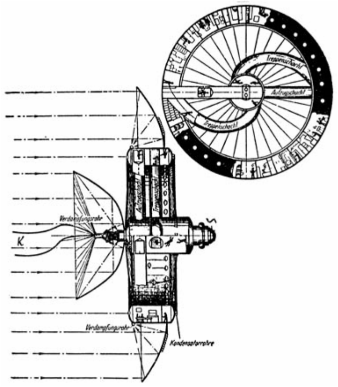

Figure 1. Der Wohnrad by Herman Noordung, 1928

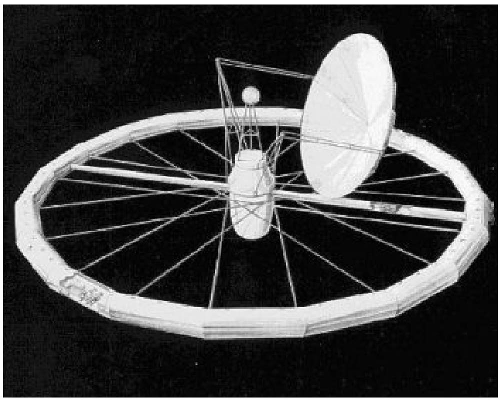

Figure 2. von Braun, 1946

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[*] "The Rocket into Planetary Space"

[†] Also known as Herman Noordung

[‡] "The Problem of Space Travel: The Rocket Motor"

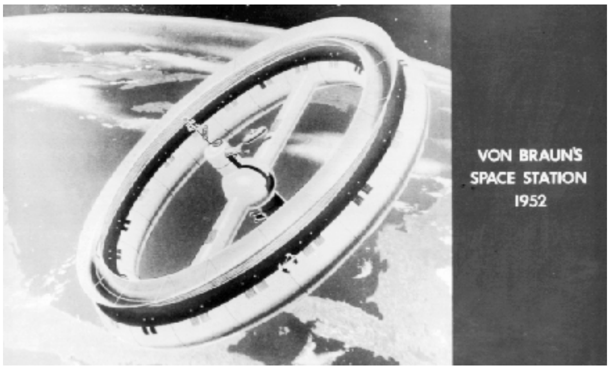

Figure 3. von Braun, 1952

Figure 4. Stanley Kubrick "2001"

In 1975, the NASA summer study presented a 1 mile diameter donut habitat called the Stanford Torus (See Figure 5). With one rotation per minute an Earth-like 1-g environment was supporting the lives of 10.000 inhabitants. The huge size of the habitat was proposed to simulate normal life on Earth (See Figure 6).

Figure 5. Stanford Torus, external artist rendering

Figure 6. Stanford Torus, internal artist rendering

Not before the beginning of the space race, by the launch of Sputnik in 1957, were humans considered a priority in space and NASA started several artificial gravity projects to define the comfort criteria's of rotating habitats. But in the coming decades the scientific potential of weightlessness was discovered and NASA's AG projects were slowly cancelled. Since the 70ies there have been few studies on artificial gravity habitats but it remained low priority.

Technical requirements

It is important that any design solution offering AG must be fully integrated with existing or dedicated launch systems, technical requirements, mission scenarios and will accommodate human comfort criteria's to a level were such a system does not require other countermeasures to endure. Furthermore, AG systems generally add costs and complexity to existing systems due to advanced engineering, danger of accidents, cost, vibration, Coriolis forces, docking difficulties, extra energy consumption and attitude control problems.

Comfort criteria's

Defining the comfort criteria's for humans in an AG habitat require an understanding of the environment. Artificial gravity is done by centrifugation and the most important parameters are angular velocity (Ω), radius (R) and acceleration (g). Increasing angular velocity (Ω) will increase the acceleration (g) as well as increasing radius (R), with steady angular velocity (Ω), will also increase the acceleration (g). From the center of the rotation to the edge there is a linear gravity gradient starting from 0g. Increasing radius (R) will result in a decrease in the gravity gradient on the human body (See Figure 7). Figure 8 shows some relations between angular velocity (Ω), radius (R) and acceleration (g). Acceleration g is also referred to as g-load.

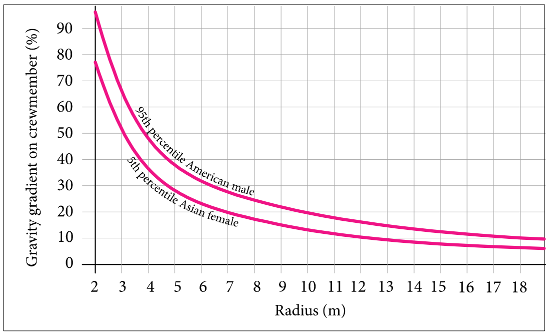

Figure 7. Gravity gradient on crewmembers with relation to rotational radius

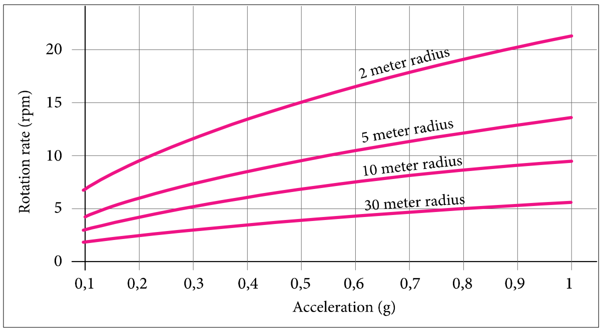

Figure 8. The relationship between radius, acceleration and rotational rate

Being in an AG environment will be a strange experience. Moving in the direction of the rotation will decrease your total speed and provide a lower g-load. Moving against the rotational direction will increase your total speed and provide a higher g-load [15]. A serious side effect from being in a rotating environment is cross-coupled accelerations produced when moving across the angular rotational forces. These cross coupled accelerations, known as Coriolis forces, can give inappropriate vestibular ocular reflexes (VOR), illusory-tilt (IT) and motion sickness (MS) [2]. Lower radius as well as higher angular velocity will increase the chances of Coriolis forces and its side effects. The rotational threshold needed for creating VOR, IT and MS by Coriolis forces is from 4-6 rpm* and with an upper limit without significant training of 10 rpm [12]. The Coriolis forces are critical to maintain at a minimum to ensure a healthy crew, capable of working maximum hours. In theory, undesirable effects of Coriolis forces will not be a problem if crew head movement remains in the plane of the rotating environment [15].

There are different opinions on what makes a comfortable AG environment. Most literature has based their final parameters for conventional living with 24 hour AG exposure to the crew. Table 2 lists an overview of earlier literature and comfort parameters for such an approach [16]. Table 3 shows the comfort parameters from a NASA AG study on a similar approach in 1971 [17]. Nevertheless, it is important to recognize that final parameters must be based on specific mission scenarios, actions performed in the rotating environment as well as duty cycles and the g-load requirement.

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* Rotations per minute

Author	Min. R	Min. V	Min. g	Min. rpm
Hill & Schnitzer (1962)	14.6	6.1	0.26	4.0
Gilruth (1969)	12.2	6.0	0.30	4.7
Gilruth "optimum" (1969)	67.1	14.0	0.30	2.0
Gordon & Gervais (1969)	12.2	7.3	0.45	5.7
Stone (1973)	15.2	10.2	0.69	6.4
Cramer (1985)	23.3	7.3	0.23	3.0

Table 2. Earlier comfort parameters from literature. Compiled by Theodore W. Hall [16]

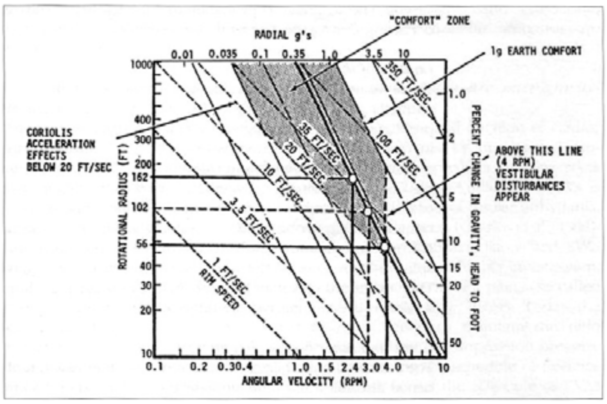

Table 3. Earlier comfort parameters from the NASA AG study 1971

Short radius centrifugation and adaptation

A different approach to having a 24 hour Earth-like environment as requirement would be creating an AG system that is within the limits of today's mission architecture. Studies at the Man-Vehicle Lab (MVL) at MIT[*] in 2001 presents short arm centrifugation as a viable solution. Subjects exposed to this AG in a SAC system show remarkable ability to adapt to both MS, VOR, IT and tumble by repeated use at rotational speeds below 10 rpm. Adaptation is especially important to avoid renewed MS when shifting between the 0g and the AG environment. Pre-adaptation from Earth for the astronauts, would provide an even smoother transition [1]. The adaptation test where done by forcing VOR, IT and MS by 90 degrees from nose-up to left-ear-down head movement. Furthermore, the conclusions from the MVL study (2001) states that in a 0g environment the adaptation could perhaps be faster and more sustainable.

The MVL study (2001) were performed with all participants placed supine on the short arm centrifuge with their head below the rotational center which is the configuration this design study will inherent.

Impact parameters

It is equally important to known the values of effective AG. Effective AG means AG that has a positive countermeasure impact on either the human body or performance. At this point, exact values of effective AG to maintain adequate Earth-based functions are unknown as well as values to postpone IP for individual missions.

From a medical point of view it might not be necessary to maintain an Earth-like status of the body if living and working on Mars require less and it is possible to regain all body-systems when returned to Earth, but full body maintenance is preferred from an ethical perspective.

We know that 24 hours exposure to 1g is adequate but as stated earlier; limitations and difficulties in integrating such a system to existing mission architecture inspire to know more other g-load potentials and alternative duty cycles. Hyper and hypo-g in various dusty-cycles might also be feasible. The HUMEX study by ESA suggest countermeasure by g-load exposure of 2-3g 1-2 hours a day [8]. The trend in the literature is the same: the relation between the amplitude and duty cycle is proportional reverse to each other.

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[*] Massachusetts Institute of Technology

Test on turtles in space exposed to 0.3g showed no muscular changes compared to ground based references [12] and test on slime-molds shows a gravity response in their cell from 0.1g [18]. Even though this data presents an indication that g-load below 1 Earth-g has potential for activating stress on the body for countermeasure none of this data is conclusive and cannot be directly transferred to humans.

When positioned perpendicular to the tangential velocity, the gravity gradient is also a significant factor directly related to the radius, as shown in Figure 7. It is important to make sure that the gradient g-load exposure on the human body is within the medical requirements or that part of the body is within the requirements, if this is adequate to support the medical improvement. Especially the medical reaction of a human body exposed to gravity gradient is not well understood.

As a conclusion this design study will incorporate the possibility to have a variety of g-load exposure and duty-cycle possibilities.

IV. Mission scenario

The crewed mission for this design study will be a 963 days mission to Mars with a crew of 6 people traveling approximately 7 month towards Mars, stay for about 533 days and travel 7 month back to Earth. Figure 9 shows the trajectory and suggested dates taken from the ESA Human Mars Mission study [19]. In total, the crew will be exposed to low gravity the entire mission with about 14.5 month in 0g and 533 days in Mars´ 3/8-Earth gravity. Assembly of the entire transit ship will likely be performed in LEO* and all parts will be launched from Earth using the new launcher system suggested by NASA's Exploration Systems Architecture Study Team (ESAS)† (See Figure 10) [3]. These new launchers provide better launching capabilities in terms of mass and diameters. Table 4 presents a short mission overview.

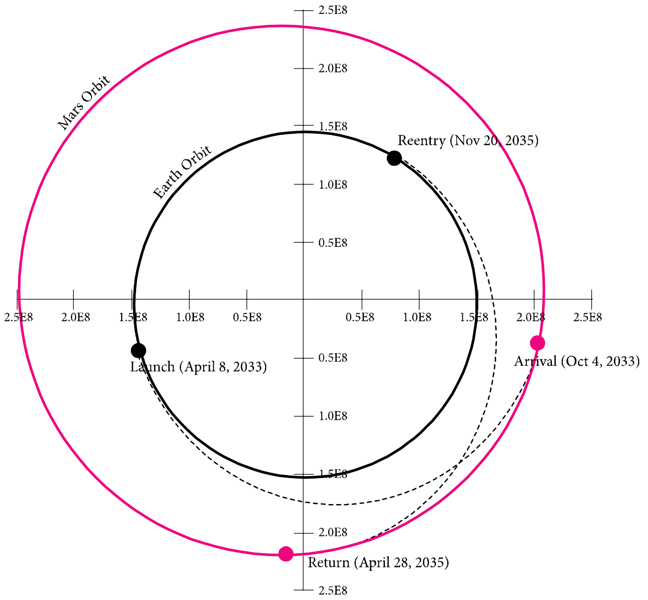

Figure 9. Possible mars mission trajectory

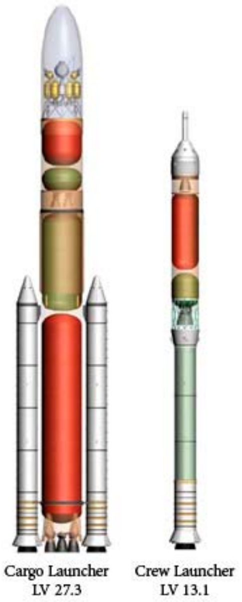

Figure 10. ESAS Launchers

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[*] Low Earth Orbit

[†] as part of the New Vision for Space Exploration presented Jan 2004

Mission scenario	
Mission type	Crewed Mars mission
Crew size	6
Total mission duration	963 days [19]
Possible surface duration	533 days [19]
Possible weightlessness duration	430 days [19]
ΔV requirement	8368 m/s [19]
Total pressurized volume	480 m^3 [19]
Launcher cargo	LV 27.3 [3]
Launcher, cargo envelope (D,H)	7467 mm, 12009 mm [3]
Launcher Crew	LV 13.1 [3]
Launcher, crew envelope (D)	5000 mm [3]

Table 4. Mars mission architecture overview

V. Integration of SRC

Duty cycles

Not knowing the duty-cycle requirements, 10 generic options of SRC duty-cycles scenarios are proposed in Figure 11.

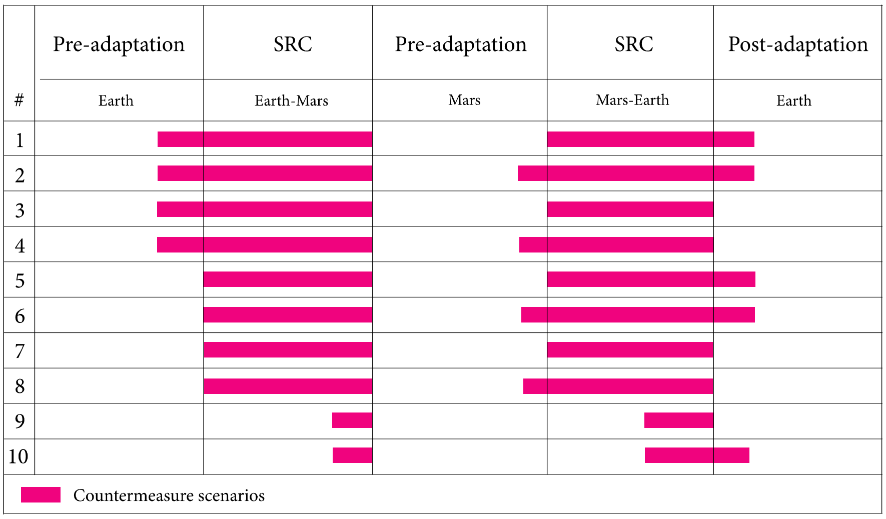

Figure 11. Possible duty-cycle scenarios. Time frames not in proportions

Scenarios 1-8 all contains continuous use of SRC in flight in comparison to scenarios 9,10 which only provide a necessary adaptation to g-loads for planetary bodies before landing there. Since Mars only has 3/8 Earth-g the required time for adaptation before landing on Mars would probably be less (or with lower amplitude) in comparison to the time required before descending to Earth. Scenarios 1-4 contain pre-adaptation to the rotation environment from Earth, in order to provide smoother transition between 0g and AG. This pre-rotation adaptation is also provides in scenarios 2,4,6,8 from Mars, but require additional mass for Mars-based equipment. Scenario 1,2,5,6,10 provide post-flight adaptation to SRC or further countermeasure against the prolonged exposure to weightlessness. Since scenario 9,10 only provide short time use of SRC, the integration of a SRC system should be justified by having a secondary purpose.

SRC sleeping module

In earlier studies by Peter H. Diamandis at MIT (1987) a short arm centrifuge called 'the gravity sleeper' was presented for weightlessness countermeasure [5]. The basic idea is to utilize the sleeping period for countermeasure, making this monotonous and tedious task easier and would provide more time for other tasks during the hours awake. A crew member was placed supine with the eyes in the center of rotation providing 0g in the head and a 100% gravity gradient. The system was supposed to produce 1g by the foot plate with 23 rpm. Such a system would not only induce massive stress to the ocular-vestibular system resulting in motion sickness due to high rotational rate, but also generate 0g and no significant countermeasure in the head region.

The combination of the SRC system with sleeping duties will be incorporated in this design study, but in contrast to 'the gravity sleeper' the design proposed in this paper will utilize the available radius as much as possible in order to provide a minimal gravity gradient. Based on the diameters available by the LV 27.3 launching system the maximum radius of our AG system can be app. 3.5 meters if we use a non inflatable rigid structure. Furthermore, by doing so we can be rewarded a 1 meter radius center space for access to the SRC system (See Figure 12) and still have room for the entire crew. Such a solution provides more freedom in the overall configuration because the SRC system will not become a dead end, blocking access to other connected modules.

To keep a free center for access, the motor system to drive the rotation will be placed between the inner walls of the transit module and the outer rim of the SRC system. The additional space required for this gives us app. a 3.3 meter radius by the foot rim of the astronauts providing g-load option as presented in Figure 13.

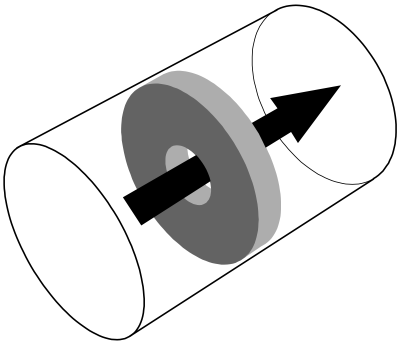

Figure 12. SRC system in transit module with center access

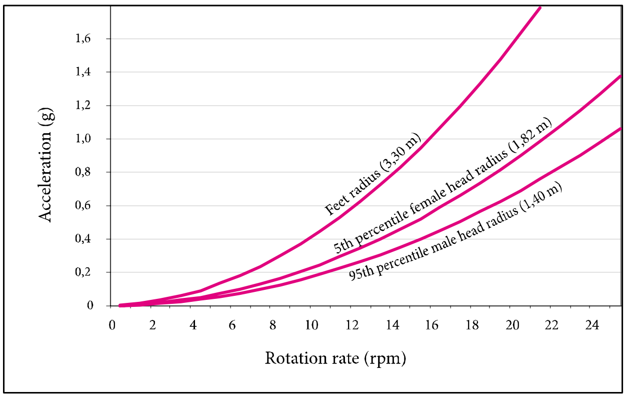

Figure 13. Acceleration curve based on the available radius

Configurations

Figure 14 presents a top view of the general configuration of the rotation platform, which will become a complete enclosed rotating room to avoid visual disturbances. Especially the aspect of privacy, not only while sleeping, but also the option of when and where to sleep must be addressed in the design. Crewed flight missions, as we know them today, have a detailed scheduling for all astronauts called the Onboard Short-Term Plan (OSTP). We must expect to still have some kind of daily planning in a long duration mission, but it might not be as strict to ensure some flexibility for the crew. Such flexible scheduling will likely include the sleeping hours which it why different SRC configurations is presented.

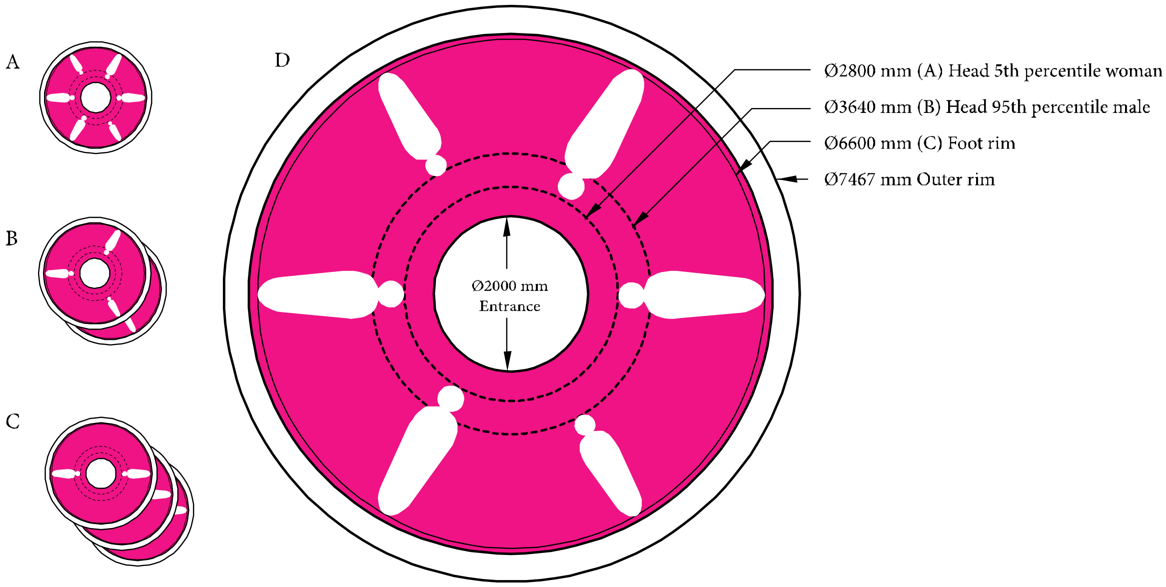

Figure 14. Basic SRC design configurations

This basic design configuration provides room for astronauts to endure countermeasure task while sleeping or as a short term task. It will provide interior flexibility to meet the requirements of international crewmembers height and weight [7].

Configuration A (See Figure 14) is a single SRC system for all 6 crewmembers. Configuration B (See Figure 14) is a double SRC system with 3 crewmembers in each. Configuration C (See Figure 14) is a triple SRC system for two crewmembers in each. All the three option are based on equal mass distribution to maintain rotation stability.

Figure 15 shows an illustration of a possible integration of configuration A and B into a transit module.

Counter rotation

A SRC in use will rotate the entire ship due to the angular momentum. Attitude control of the ship is critical and any counter rotation must react upon the total angular momentum product from all SRC systems either by rotation wheels, a neighbouring SRC or a combination of both. It is worth considering using counter rotation between two or three SRC systems if these configurations are chosen, (See Figure 16). Even adjustment in the SRC rotational speed can be considered for attitude control, but it should not result in any medical of functional side effects and work within the countermeasure requirements. However, counter rotation by the SRC modules will result in double the rotational speed in the center area between the two SRC systems, were free passage must be allowed. It becomes critical to investigate the detailed design and use of this region in order to maintain safety and easy ingress/egress from outside the SRC configuration to the second SRC system.

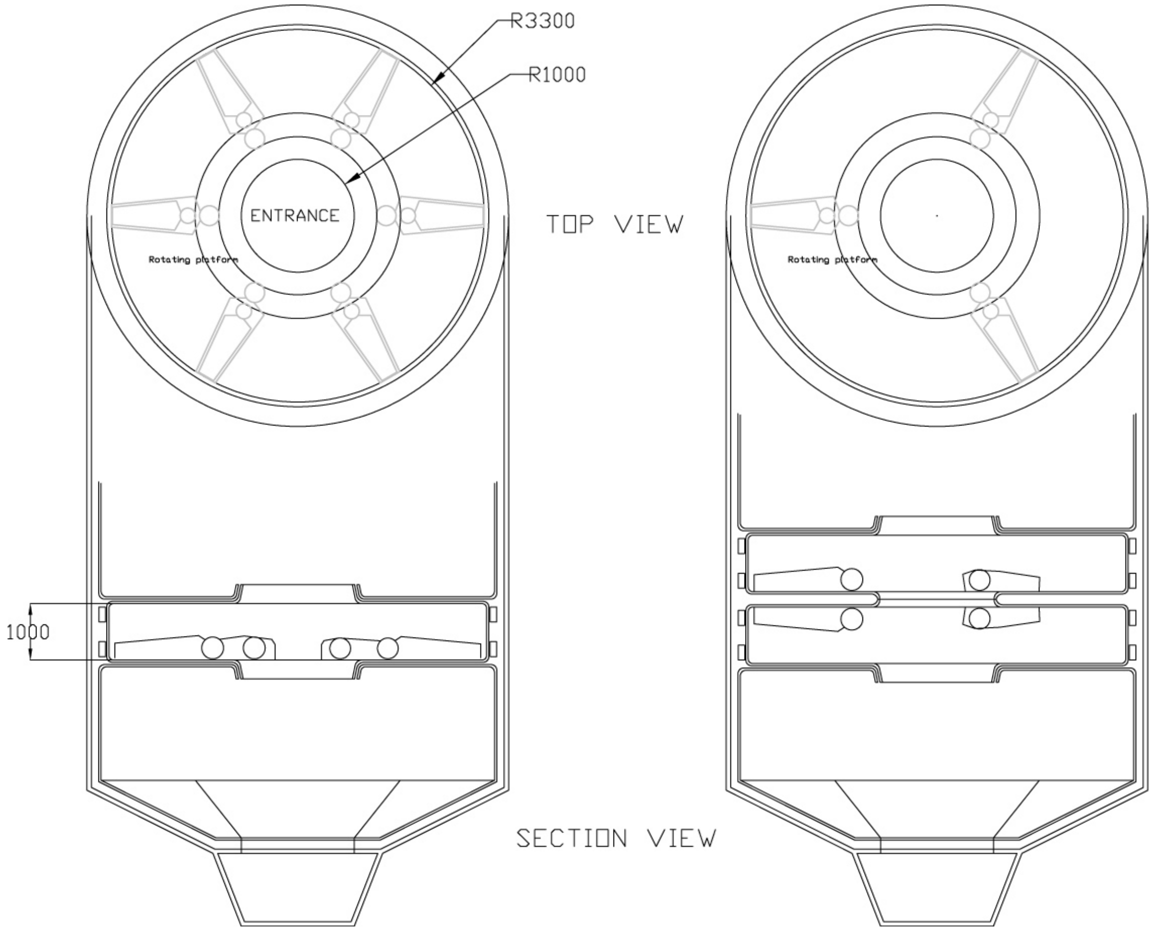

Figure 15. Top and section view of single and double configuration of SRC in transit module. Measurement in mm. Not in scale

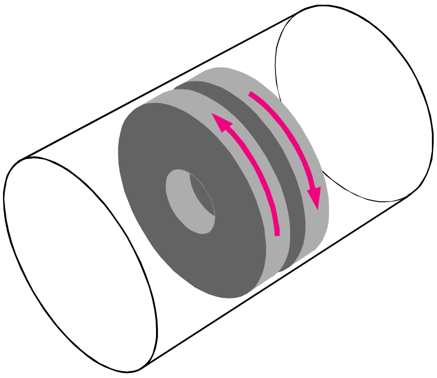

Figure 16. Double SRC configuration with counter rotation for attitude control

Ingress / egress

Only the edges of the rotation center should be visible from outside the SRC. On the other hand it is important that the rotation of the SRC system can be easily seen from the outside to avoid any injuries and surprises. Each private quarter must be easy to ingress by a soft handle that rotates slowly with the entire system. By reaching a handle you will start to rotate with the SRC and can ingress a private zone with 0 speed differences to the system (Figure 17). However, such an approach must only be considered in a slow rotating mode (10 rpm and down).

Once inside the SRC, a crewmember can don a sleeping bag or other restrains as well as egress the SRC by reaching the handle and pull herself outside.

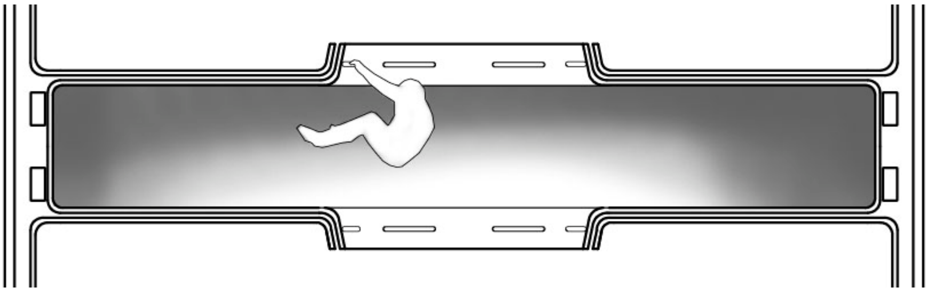

Figure 17. Easy access procedure in single SRC configuration

SRC use and head activities

As mentioned earlier in this paper, Coriolis forces are important to keep at a minimum to avoid motion sickness and illusory tilt amongst the crew members. To meet this requirement we can take advantage of several methods. The SRC system could be use at rotational speeds that does not provoke these side effects or minimize crew members head movements.

In any case, a critical part is the movement of the head while rotating which will require head- and neck support-equipment inside the SRC system. This neck support system must ensure a comfortable rest-bay, adjustable for all head shapes and sizes and use of pillow. The neck support will also be adjusted accordingly to the heights of the crew members insuring foot rest on the foot rim for maximum g-load.

Crew members will have the opportunity to sleep with their heads facing upwards or to any side since MS, VOR and IT are only experienced during fast head movements at certain rotational speeds. How crew members will react to uncontrolled head movements during sleep is unknown.

A generic sleeping bag could be used with restraints inside the SRC. The restraining and the sleeping bag will insure unnoticed transformation of the rotational forces to the body. Walls and ceiling inside the SRC is connected as one enclosed space providing no visual information of rotation in relation the entire transit module.

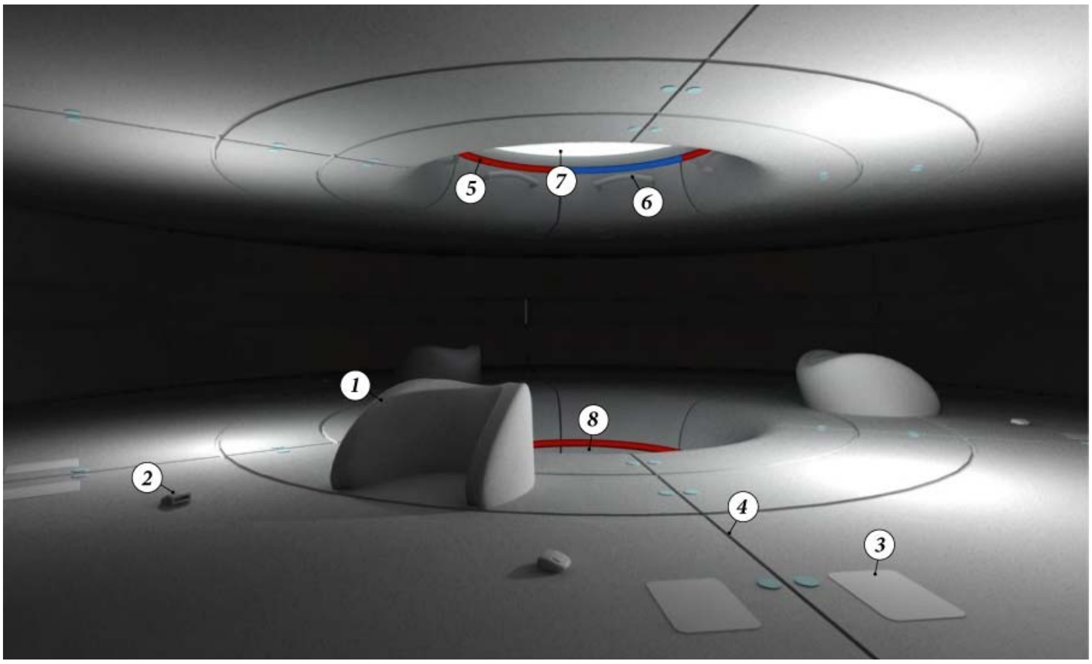

Figure 18. Interior rendering of SRC sleeping area without separation walls.
1. Adjustable neck support, 2. Restraint, 3. Hatch to emergency stop, 4. Flexible wall zone,
5. Occupation light, 6. Ingress / egress handle, 7. Exit to living area, 8. Access to second SRC

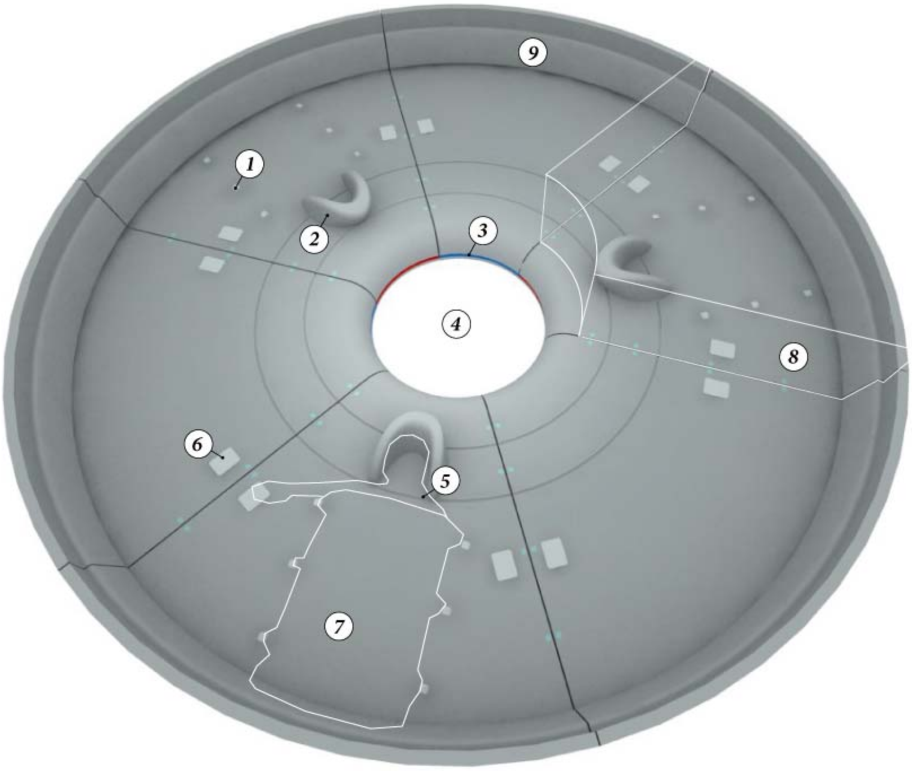

Figure 19. Rendering of SRC system, presented with transparent top.
1. Sleeping bag restraint, 2. Neck support, 3. Occupation light, 4. Ingress/egress,
5. Crewmember, 6. Emergency stop pad, 7. Sleeping bag, 8. Flexible wall area, 9. Foot rim

VI. Environmental considerations

There are several important factors to be considered as part of further development.

Light, noise and air

Inside SRC, light conditions are important for privacy issues and comfort while sleeping and performing short term countermeasure. Colored light could be used to create a supportive atmosphere for the crammed space as well as being part of the information system, telling if cabins are occupied or if the SRC is moving.

Noises, produced by the SRC system or the entire ship, are important to control in order to insure a comfortable environment. Also sound insulation, between the private areas, is important to incorporate in a flexible cabin separation system.

Fresh air, humidity and ventilation are important issues to insure healthy crewmembers. Personal control of temperature would be preferred, but is a challenge.

VII. Discussion

Based on the mission scenario, possible g-loads and comfort criteria's from literature, a generic design was proposed to support the idea of a short radius centrifugation for weightlessness countermeasure. Throughout the paper there were no conclusions on a final design but rather opportunities for future decisions, when more detailed data is available.

At this point, only the radius of the SRC system is a fixed parameter of 3.3 meters, based on the launching system. The radius provides us with the relation between the angular momentum and g-load as presented in Figure 13. Further decisions on the angular momentum, duty-cycles and scheduling should be based on conclusions from the medical science community. However, such conclusions may present more than one option where both short- and long duty-cycles are useful depending on amplitudes and schedules as suggested in Figure 11.

Should a short duty-cycle be chosen (e.g. 1-2 hours/day with 2-3g) the single configuration (Figure 14.A) will perhaps be the best choice because all 6 crew members will ingress the SRC system simultaneously, as any other task, with no special need for privacy. Furthermore, if the task will be scheduled for as preparation for g-load change for planetary bodies (Figure 11, #9-10), a secondary purpose of the SRC should be proposed to utilize the space and mass for the entire mission. Such a secondary purpose could be sleeping quarters. But, the question is if the crew is interested on using the SRC as their private sleeping quarters if there are benefits and more privacy in sleeping somewhere else on the ship?

Should a long duty-cycle be chosen (e.g. 7 hours), one must perform the privacy vs. Engineering/mass trade-off study because such a system should be used while sleeping. A single-SRC system (Figure 14.A) provides the easiest ingress/egress and the lowest mass and complexities. However, the lack of flexibility in sleeping options for the crew might not be a good choice for a long duration space flight. Furthermore, the single configuration provides the least privacy even with sliding wall separation. From a functional point of view the crewmembers do not need more space, but sleeping very close to each other could provoke irritations from noise, humidity and other bodily parameters. Not providing enough flexibility for crew might not be a good solution for crew moral.

That flexibility can be provided by the double-SRC system (Figure 14.B), but such a system requires more mass and has less utilized space. The double SRC configuration will support two groups who can decide when to sleep and such a solution might provide enough flexibility to avoid the feeling of forced sleeping duties. Access to the second SRC system also becomes more difficult.

A triple SRC configuration (Figure 14.C) provides even more flexibility for the entire crew but also require very larges masses with almost no utilization of the large free space. The triple SRC configuration would be difficult to justify.

Both the double and triple SRC configuration can be utilized as part of the attitude control system, but such a benefit might not justify the additional mass from these systems.

Table 5 lists the cons and pros of the configurations Figure 14.A-C.

Requirement	Single-SRC	Double-SRC	Triple-SRC
Mass	Lowest	Medium	Maximum
Engineering complexity	Lowest	Medium	Maximum
Space utilization	Maximum	Low	Very low
Private sleep scheduling option	Bad	Medium	Good
Privacy	Minimum	Good	Very good
Ingress/egress	Easy	Complex	Very complex
Possible best scenario?	Short duty-cycles (1-2 hours)	Long duty-cycles (7+ hours)	-

Table 5. Pros and Cons of design configurations show in Figure 14

VIII. Conclusion

It is clear that further investigations on g-loads and duty-cycles requirements are needed. Before any conclusions from the medical scientific community have been presented it is not possible to make any final conclusions for the engineering requirements and to present a final design.

Nevertheless, the presented design study shows that there are a variety of options, within the same generic configuration, to satisfy any future decisions for countermeasure against prolonged effects of weightlessness.

References

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[1] Steven T. Moore et al., 2005. Artificial Gravity: A possible countermeasure for post-flight orthostatic intolerance. Acta Astronautica, No. 56, pp. 867-876

[2] Laurence R. Young et al., 2001. Artificial Gravity: Head Movement during Short Radius Centrifugation. Man-Vehicle Lab, Massachusetts Institute of Technology. Acta Astronautica, No. 3-10, pp. 215-226

[3] NASA ESAS Final Report, November 2005: Section 6.0, Launch Vehicles and Earth Departure Stages.

[4] Theodore W Hall, August 1999. Artificial gravity and the architecture of orbiting habitats. Journal of British Interplanetary Society, Vol. 52, No. 7/8, pp. 290-300

[5] Peter H. Diamandis, October 1987. Reconsidering artificial gravity for twenty-first century space habitats. Space Manufacturing 6, Nonterrestrial resources, biosciences and space engineering, Eight Princeton/AIAA/SSI Conference, pp. 55-68

[6] Charles M. Oman, Feb 1986. Spacelab experiments on space motion sickness. Acta Astronautica, Vol. 15, pp. 55-66

[7] NASA, July 1995. Man-Systems Integration Standards. Revision B. Section 4.4, Olfaction and taste

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[8] European Space Agency, November 2003. SP-1264: HUMEX Study on the survivability and Adaptation of Humans to Long-Duration Exploration Missions, pp. 73-79
[9] Titov Vladimir, Encyclopedia Astronautica. http://www.astronautix.com/astros/titdimir.htm. Updated NA
[10] NASA daily timelines for ISS. http://www.nasa.gov/mission_pages/station/timelines/index.html. Updated March 7, 2006
[11] Philipe Meliga et al., March 2005. Artificial Gravity – head movement during short-radius centrifugation: Influence of cognitive effects. Acta Astronautica, Vol. 56, pp. 859-866
[12] Harold Sandler, 1995. Artificial Gravity. Acta Astronautica, Vol. 35, No. 4/5, pp. 363-372
[13] Herman Potocnik Noordung. http://noordung.vesolje.net/vsebina/station.htm. Updated NA
[14] Von Braun Station. http://www.astronautix.com/craft/vonation.htm. Updated NA
[15] Ashton Graybiel, 1977. Some physiological Effects of Alternation between zero gravity and One gravity. Space Manufacturing Facilities, pp. 137-149
[16] Theodore W. Hall, 2002. Architectural Considerations for a Minimum Mass, Minimum Energy, Artificial Gravity Environment. 32nd International Conference on Environmental Systems. SAE International. 2002-01-2431
[17] NASA, 1971. Habitability Data Handbook, Vol. 1, MSC-03909
[18] NASA, July 1997. Second International Microgravity Laboratory (IML-2) Final Report, pp. 151
[19] European Space Agency, Feb 2004. Cdf Study Executive Summary - Human Missions To Mars - Overall Architecture Assessments. CDF-20(C)

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