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Dormancy Should Be Avoided for Mars and Deep Space Recycling Life Support

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Mars is the crucial goal of human exploration beyond the Earth-moon system. The Mars round trip transit vehicle has been expected to use a regenerative Life Support System (LSS) similar to the one on the International Space Station (ISS). It often assumed that the Mars transit LSS will be operated on the outward trip to Mars, placed in dormancy while the full crew explores the surface, and then restored to operation for the return trip to Earth. The major difference between Mars missions and operations in the Earth-moon system is the need for much higher reliability for Mars missions, since rapid resupply of parts and materials or a quick crew return to Earth are not possible. Mars systems must achieve intrinsic high reliability by design, test, failure analysis, and redesign and then increase operational robustness by providing spare parts and redundant systems. Further requiring the LSS to be capable of dormancy and restoration to operation greatly increases the difficulty of design, test, and verification. The process of implementing dormancy and then restoring operation would add significant risk to the mission. Dormancy should be avoided for Mars and can be avoided several ways. First and most obvious, some crew can remain continually on board. If no crew can remain onboard, dormancy can still be avoided if an unused spare LSS is activated for the return trip, rather than restarting the used out bound system. Systems similar to the ISS LSS would have a significant probability of failure on a Mars trip and therefore would require two or three spares. Another full spare LSS could be provided as the return trip system, rather than refurbishing a used LSS.

Nomenclature

ECLSS	=	Environmental Control and Life Support System
ESM	=	Equivalent System Mass
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LiOH	=	Lithium Hydroxide
LSS	=	Life Support System
ORU	=	Orbital Replacement Unit

I. Introduction

DORMANCY should be avoided for recycling life support to minimize risk on a human mission to Mars. Life support dormancy is a period of nonoperation between two periods of operation. Designing for dormancy would add significant cost and complexity. The operations of preparing for dormancy and restoring operations can require significant time and substantially increase mission risk. One benefit of dormancy, allowing all the crew to leave microgravity and explore the surface, can be obtained by a mid-mission crew rotation between the orbiting transit craft and the surface. Another benefit of dormancy, saving cost by reusing the same hardware, is largely illusory. The system used out bound has relatively little value since the major cost of round trip hardware is the propulsion cost to send it back from Mars to Earth.

The expectation for Life Support System (LSS) dormancy is based on two clearly stated assumptions:

1. Deep space missions will require LSS dormancy, meaning that operating systems will be left inactive and unattended and later restored to service. (Carter and Tabb, 2015) (Carter et al., 2017) (Sargusingh and Perry, 2017) (Williams-Byrd et al., 2016)

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2. A reference LSS architecture, similar to that in the current International Space Station (ISS), will be used. (Carter and Tabb, 2015) (Carter et al., 2017) (Howard et al., 2015) (Sargusingh and Perry, 2017) (Williams-Byrd et al., 2016)

There is also a third unstated assumption:

3. There will be only one LSS, so the LSS to be used on the return trip, after dormancy, is the same one used outbound.

Dormancy can be avoided if any one of these three assumptions is not accepted. The corresponding three ways to avoid dormancy are:

1. Keep some crew always on board, as in Apollo.
2. Use a new spare LSS after the crew return, not the previously operated system.
3. Use stored life support materials, such as water and oxygen, rather than providing recycling systems.

II. Dormancy increases risk

It has been assumed that on a human mission to Mars, all the crew will descend to the surface and the transit habitat LSS will be placed in dormancy. However, this would require extensive modification of the LSS and would add three new operational risks to the mission; preparation of systems for dormancy, possible problems during dormancy that might require crew presence, and restoration of operation. The most significant mission risk is the probability of loss of crew, which could occur through loss of the LSS, and dormancy requires operations that increase this risk. Work on dormancy considers many of these risks. (Carter and Tabb, 2015) (Carter et al., 2017) (Sargusingh and Perry, 2017)

As NASA work on dormancy makes clear, designing for dormancy could be very difficult. (Howard et al., 2015) (Williams-Byrd et al., 2016) Preventing microbiological contamination of the Water Recovery System is a serious problem, and it may be better to simply replace some components and piping. (Carter and Tabb, 2015) (Carter et al., 2017) However, some systems are usually cycled and could simply be turned off and turned on later, such as the carbon dioxide removal system. (Sargusingh and Perry, 2017) Others such as heaters and ventilation can remain active in a dormant phase. (Sargusingh and Perry, 2017) But the difficulties noted by these authors make it seem that dormancy should be avoided. More detail on the risk of dormancy is provided in an appendix.

III. Risk should be avoided

NASA's manned space programs have had two drastically different approaches to risk. After the tragic Apollo 1 fire, and calculations suggesting than many astronauts would die before one reached the moon, NASA became obsessed with reducing risk. Apollo suffered no further loss of life because the system and every participant far exceeded expectations. It was thought that the Apollo risk analysis was too pessimistic and too negative for the program, so risk analysis was discontinued. (Bell and Esch, 1989) This led to an unnecessarily risky shuttle design, which directly caused the Challenger and Columbia tragedies. (Jones, 2018-5235) The clear results of the Apollo respect for and shuttle neglect of risk suggest that NASA and life support should place great emphasis on reducing risk. Dormancy introduces significant design and operational risks. Risks must be rigorously minimized to ensure crew safety. To minimize risk, dormancy should be avoided for deep space life support.

Contrary to this, it has usually been assumed that life support will be placed in dormancy. This suggests that risk, reliability, and safety should receive more emphasis in life support. For decades, the major metric and decision factor in advanced life support analysis has been Equivalent System Mass (ESM), which combines the hardware mass with the mass of the pressurized volume, power supply, and cooling system needed to support it. ESM does not specifically consider reliability and safety. Advocates of using a life support architecture similar to the ISS ECLSS have incorrectly minimized the reliability problem by suggesting that such systems can be maintained successfully on a trip to Mars simply by providing spares. Relying on spares is successful only when failure rates are known accurately enough that an adequate number of spares can be provided with certainty. Unfortunately, new or redesigned systems such as the ISS ECLSS always have some components with unexpectedly high failure rates, and in this case the computed number of spares would be insufficient. (Jones, 2017-86)

IV. Should some crew remain onboard?

In order to reduce risk, Apollo had one crewmember remain in orbit orbiting the moon while the other two explored the moon's surface. Although having a single crewmember on board would eliminate the risk of dormancy, long continued zero gravity and isolation would add risks for the remaining crewmember. Perhaps having two teams of two crew alternating between the surface and the orbiting spacecraft would be better.

V. Should life support use a new spare system for the return trip?

If the crew all departs to the Mars surface, can LSS dormancy still be avoided? LSS system dormancy is a period of nonoperation between two periods of operation. An unused stored system is new and would not be considered dormant. Using a new stored LSS for the return transit rather than restarting the one used outbound would avoid dormancy.

What would a new stored LSS cost? System mass is the traditional cost metric used in early mission concept planning. If only one LSS was needed for the round trip, using one outbound and one on the return would double the mass, but it is not possible to have only one LSS. Systems similar to the ISS LSS would have a significant probability of failure on a Mars round trip, typically 10%. (Jones, 2017-85) Spares are needed to ensure crew safety. The NASA Astronaut Office requested that future launch vehicles have a probability of loss of crew of at most 1 in 1,000 flights, which was a roughly order of magnitude decrease from the then operational space shuttle. (Memo CB-04-044, 2002) One way to achieve sufficient reliability is simply to provide three full LSS's. The probability of all three failing is 0.1 cubed or 0.001, 0.1%, 1 in 1,000. Another fourth full LSS could be provided for the return trip. This would increase total mass by one-third if the fourth LSS made the round rip, but the used out-bound system does not need to make the round trip back to Earth. It could be allowed to continue on its Earth-Mars trajectory and fly by Mars to save the return propulsion mass and cost. If there is one additional LSS, dormancy is not needed.

A problem with using complete unrepairable LSS's is that a single failure would require replacement of the entire system. A better approach is to have the LSS's use interchangeable subsystems to allow repairs. The ISS ECLSS and most ISS systems use ORUs (Orbital Replacement Units) to repair failures. Enough ORUs are kept on board that there is usually a very small probability, a few percent, of not having one when it is needed. This means that most ORUs will never be used; they are insurance.

Table 1 gives the masses of the ISS ECLSS systems, of a single set of spare ORUs, and of a full system plus three sets of spares. A complete LSS similar to the ISS ECLSS with the required three spares would be the baseline system for Mars transit. Without an additional fifth return transit LSS, this baseline system would have to be designed for dormancy to ensure having an operating system and three spares.

Table 1. Hardware masses and hardware plus propulsion masses for the ISS ECLSS in Mars transit.

System	System mass, kg	One set of spares mass, kg	Hardware mass of one system and three spares, kg	Hardware and round trip propulsion mass of one system and three spares, kg	Hardware and propulsion mass of one fly-by system, one return system, and three return spares, kg
Mass gear ratio				12.2	3.6, 12.2
Oxygen Generation System	676	399	1,873	22,851	25,284
Carbon Dioxide Removal Assembly	195	156	663	8,089	8,791
Carbon Dioxide Reduction System	329	219	986	12,029	13,214
Water Recovery System	1,383	719	3,540	43,188	48,167
ISS ECLSS	2,583	1,493	7,062	86,156	95,455
Mass ratios	0.37	0.21	1.00	12.20	13.52
Mass ratios				1.00	1.11

The ISS ECLSS total system and spares masses in Table 1 are from Jones, 2017-85, Appendix A. That paper calculated the mass of a system plus its needed spares under three different assumptions: with three spares for each ORU, with the spare ORUs needed for a 0.001 failure rate based on an initial ISS failure data base, and with the spare ORUs needed for a 0.001 failure rate based on flight failure rates. The total spares mass results were similar in all three cases, so only the case with three spares is used here. (Jones, 2017-85)

Table 1 also gives the total hardware and propulsion mass to use different numbers of systems and spares on Mars transit. A rocket's stack-to-payload mass ratio or gear ratio is the ratio, of the total payload mass plus rocket mass plus propulsion mass that is needed in LEO to emplace the payload mass at its destination, to the payload mass. To send a system to Mars and let it fly by without being aero-captured into Mars orbit has a gear ratio of 3.6. To take a system out of Mars orbit and sent it back toward Earth and ultimately past Earth has a gear ratio of 3.4. Assuming that aero-capture into Mars orbit has a negligible propulsion cost, the gear ratio of a Mars round trip is 3.6 * 3.4 = 12.2. (Condon et al., 2000, pp. 277-8)

Taking one LSS system and three sets of spare ORUs in LEO and sending them on a trip to Mars orbit and back past Earth increases the mass needed in LEO by a factor of 12.2. Achieving the required reliability on the return trip requires having one operating system and three spares. Adding a fourth LSS system and using it outbound but then jettisoning it and allowing it to fly by Mars would increase the total mass in LEO by only an additional 11%. This seems a small price to avoid dormancy.

VI. Should material storage be used instead of recycling?

In discussions of future deep space life support, it is usually assumed that an LSS architecture similar to the current ISS ECLSS, will be used. (Carter and Tabb, 2015) (Carter et al., 2017) (Howard et al., 2015) (Sargusingh and Perry, 2017) (Williams-Byrd et al., 2016) Direct material provision and storage rather than recycling has been used for all short missions from Apollo to shuttle, but it has always been assumed that the increasing mass and launch cost of stored materials for longer missions would force the use of recycling for longer missions where it saves launch mass.

Several facts challenge the assumption that recycling is better than direct supply for the transit to Mars. Since most systems of the ISS LSS began operation in 2008, they will ultimately have more than ten years to produce recycled material to pay back their launch cost. (Bagdigian et al., 2015-094) The transit to Mars and back usually takes less than 450 days, a year and four months. (Boden and Hoffman, 2000) Mars recycling systems have much less time to pay back their launch mass by producing recycled mass, and some ECLSS systems such as the Oxygen Generation System actually weigh more than the oxygen that they would provide during a Mars transit. (Jones, 2016-103) (Jones, 2017-87)

The material supply mass can be compared to the recycling hardware mass for a Mars transit. The amount of oxygen needed is 0.84 kg per crewmember per day. (Weiland, 1994, p. 6) About 2 kg of lithium hydroxide (LiOH) is required to remove the 1 kg of carbon dioxide each crewmember produces per day. (Eckart, 1996, p. 192) The individual crewmember requires about 5 kg per crewmember per day of water. This is based on space station analysis, except that showers, dish washing, and most of the crew hygiene water have been eliminated. (Weiland, 1994, p. 6)

Table 2 computes the mass payback of ISS ECLSS assuming four crew and a 450-day round trip Mars transit. A 10% allowance is added for tanks and containers and another 10% for spares. (Jones, 2017-87)

Table 2. Mass payback of ISS ECLSS compared to resupply for Mars transit with four crew.

Recycling mass				Supply mass			Supply/recycling mass ratio
	Single system mass, kg	One set of spares mass, kg	Hardware mass of one system and three spares, kg	Supply	Mass per crewmember day, kg/d	4 crew, 450 days, & 10% tankage & 10% spares, kg	Supply/recycling mass ratio
Carbon Dioxide Removal Assembly	195	156	663	LiOH	2.00	4,356	6.57
Carbon Dioxide Reduction System	329	219	986				
Oxygen Generation System	676	399	1,873				
Total oxygen system	1,005	618	2,859	O_2	0.84	1,830	0.64
Water Recovery System	1,383	719	3,540	H_2O	5.00	10,890	3.08
ISS ECLSS	2,583	1,493	7,062		7.84	17,076	2.42

The Carbon Dioxide Removal Assembly has a relatively low system mass and replaces a large mass of LiOH, so it pays back 6.57 times its mass over a 450-day Mars transit. Using the Carbon Dioxide Removal Assembly or similar technology on Mars transit is attractive because of the mass savings. Dormancy may be easier to implement, since this system is cycled on and off rather than being used continuously. Producing recycled oxygen requires the Carbon Dioxide Reduction System to convert carbon dioxide to water and the Oxygen Generation System to create oxygen from water. The total oxygen system weighs about one and a half times the oxygen it would produce. Oxygen generation does not save mass on a Mars transit. (Jones, 2016-103) The water system pays back three times its mass over a Mars transit, and the easiest recycling, of humidity condensate, pays back more. (Jones, 2017-85) A water system design specific to Mars transit could be designed for dormancy if needed. (Carter and Tabb, 2015) (Carter et al., 2017)

The launch mass has long been used as a cost metric, based on the idea that launch cost is a major part of total cost. The ISS was built using the shuttle and the ISS LSS design decisions to implement recycling reflect the very high shuttle launch costs. Now that commercial systems have greatly reduced launch cost, recycling must achieve much greater mass savings to actually reduce cost. NASA's space shuttle had a cost of about $1.5 billion to launch 27,500 kg to Low Earth Orbit (LEO), $54,500/kg. (Pielke and Byerly, 2011) SpaceX's Falcon 9 now advertises a cost of $62 million to launch 22,800 kg to LEO, $2,720/kg. (Spacex.com, 2018) Commercial launch has reduced the cost of sending mass to LEO by a factor of 20. (Jones, 2018-81) Since the development cost of recycling systems is very much greater than the development cost of tanks for water and oxygen, material supply seems much more cost effective that recycling for Mars transit. (Jones, 2017-87) Material resupply is also intrinsically more reliable and less in need of continual crew monitoring and maintenance.

VII. Conclusion

It would be very difficult and risky to design and implement life support dormancy for deep space. Fortunately, dormancy can be avoided in several different ways. The first most obvious way is to have some crew on board at all times. The second way, if the crew must all leave and a system similar to that on the ISS are used, is not to place the life support system in dormancy and later restore it to service, but rather to activate a previously unused system for the return transit, after having jettisoned the used out bound system on arrival. The third way, if the crew must all leave, is not to use a recycling system similar to that on the ISS, but to use simple, reliable material resupply of water, oxygen, and other materials.

Appendix: Risk awareness for life support dormancy

This appendix considers risk in space and specific risks of dormancy in life support. Many space life support participants are concerned that dormancy creates many difficult technical problems. However, specifically considering the risk of dormancy is not usual.

A. Risk in space flight

Risk is the possibility of an unfavorable outcome. Almost all actions create some risk, usually only a small chance of a minor inconvenience. On the other hand, excessive risk avoidance is overly inhibiting, preventing innovation and blocking creativity. Adventurous space exploration has much higher than everyday risk. Space advocates sometimes say, "No risk, no exploration," which is true but points to the necessary trade-off between risk and accomplishment, cost, and other factors. Those planning human space missions must understand the risk and to reduce it to a reasonable minimum. Mission and system design should specifically include risk in evaluating options and making trade-offs.

The space shuttle is the classic example of how deliberate minimization of risk can lead to taking excessive and ultimately unacceptable risks. Risk analysis was discontinued by NASA during Apollo and externally required analysis was severely distorted to minimize risk. (Bell and Esch, 1989) This reduced emphasis on risk led to launch abort capability being eliminated to increase payload and decrease launch cost, which was considered necessary to advance space exploration. (Henderson and Nguyen, 2011)

B. Risk of dormancy for life support

Spacecraft dormancy is a mission phase when the spacecraft is uninhabited but a few functions are required to maintain an adequate environment to support the vehicle systems. The dormant environmental requirements include temperature, pressure, humidity, and oxygen levels.

Risks related to life support dormancy can be explained using a concept of operations. The major operational stages are preparing for dormancy, dormancy itself, and transition out of dormancy. Different life support requirements and potential problems occur in each stage. The operations and risks have been identified in a published concept of operations for dormancy, which is the source of most of the material below. (Sargusingh and Perry, 2017)

1. Preparing for Dormancy

The transition to life support dormancy will require atmosphere pressure and composition to be maintained until the crew departs. The spacecraft modules should be isolated except for controlled intermodule ventilation, to prevent the spread of fire or a pressure loss. Provision must be made for remotely reprogramming or turning off some functions. The atmosphere pressure will be reduced to lessen leakage and will be maintained using only nitrogen to reduce the possibility of fire. Carbon dioxide removal will be turned off. Heaters and ventilation will remain on at lower set points. Relative humidity will be reduced after the crew leaves to prevent condensation at the lower temperatures. Environmental monitoring will remain active. As far as possible, water stores should be isolated and secured separately from the water recovery systems. The water recovery systems should be flushed and treated with biocide and placed in a dry standby mode. Preparing for dormancy is a complex operation with the risks that materials, parts, tools, procedures and human performance may fail to achieve the planned state of dormancy.

2. Dormancy

The major risk of dormancy is that some problem or change may occur during the unattended period that prevents a later successful transition out of dormancy. Systems that remain on, such as environmental monitoring, heating and ventilation, and systems that can be left off without obvious harm, such as carbon dioxide removal and oxygen generation if water is removed, seem capable of dormancy but require more investigation.

The water recovery system presents the two most obvious problems for dormancy and requires the most extensive preparations to prevent them. The potential problems and mitigations are:

1. Microbial growth on surfaces - cleaning, disinfection, anti-microbial coatings, reducing temperature, reducing humidity, ventilation
2. Biomass growth in water – emptying, flushing, biocide

Another major problem is degradation due the passage of time or inactivity. Materials degrade, structures deform, and seals leak. Rotating machines may seize. Sensors drift. Some hardware may be cycled during dormancy, but the water system will not be in a fully operational mode. It has been suggested that some parts of the water system be periodically operated and that others be completely replaced after dormancy. (Taub and Carter, 2015-075)

3. Transition Out of Dormancy

A habitable environment must be established before crew return. The pressure, oxygen level, trace contaminant control, and temperature control systems must be remotely reprogrammed to return their normal configurations and allowed time to reestablish the environment. After crew return, the remaining life support systems must be restored to operation and tested. The water system will probably require very extensive work. (Taub and Carter, 2015-075) As with preparing for dormancy, restoring life support is a complex operation with the risk that it may fail to achieve normal operation. Some specific risks are:

1. Failures could occur during pre-habitation atmosphere restoration, requiring the crew to work in protective gear or even space suits.
2. Chemical fluid leaks could contaminate the atmosphere, again requiring protective gear.
3. A failure of the environmental monitoring would require the crew to assume a hazardous atmosphere.
4. Despite mitigations, the water system may experience biological growth and require extensive cleaning.
5. Hazardous systems with high temperature, high pressure, or high power, such as the oxygen generator, will be a concern during restoration of life support.

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