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Life Support Systems Functional Stability and Human Control Limitations- An Astrosociological Approach

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In order to pursue space colonization, long duration spaceflight, and human missions to Mars, we will need closed ecological life support systems which provide sustainable use of limited resources. While such systems are in various stages of development, we lack knowledge regarding the functional stability of closed ecological life support systems (CES) for long-duration space missions. Our global Earth Biosphere CES functioning is based upon statistical regulations, which are provided by planetary buffers. All current deviations caused by human activity are currently absorbed by these 'planetary buffers'. Man-made Closed Ecosystems function at the limits of their natural stability due to insufficient buffer capacities and thus needs to be replaced or supplemented by other more appropriate control approaches. Previous research has indicated that purposeful control from human can increase stability levels if specific algorithms compatible to natural mechanisms are applied. Theoretical analysis is being done on data obtained in different Closed Ecosystems and has been shown that certain limits of functional stability exist for each specific system in terms of average material cycle rate and range of fluctuations. These limits are determined by: the system's buffer capacities, the slowest (basic) material cycle in the system, natural structure of the circulating chemical elements cycles and Human Factors material load. Numerical estimates are provided for carbon cycles and it has been shown that stability of cycles in man-made ecosystems are more than a thousand times less than for global planetary cycles. Human Control could increase this low level of stability tremendously, but requires a certain level of understanding for closed material cycles development inside each specific system. This presentation will primarily discuss interactions between small-scale human crews and the available limited resources required for a CES functioning. Since there are limited resources in a CES, instead of continuously increasing consumption as would be possible in an unlimited environment, self-sustainable behaviors/activities must be practiced. This paper will address the limitations for human adaptation in a space environment and how to optimize human and environment interaction in a CES. Applications to manned space exploration will be considered in the context of understanding human motivation.

I. Introduction

Although the concept of the biosphere is often thought of as a 20th century creation, the first recorded use of the term appears to go back to 1875 where Eduard Seuss, a geologist, used the phrase "biosphere" to describe "the place on earth's surface where life dwells."[1] The first person to suggest the idea of autonomous Life Support System (LSS) based on human and plant interaction for long-term space missions was Konstantin Tsiolkovsky in his 1903 paper "The Exploration of Cosmic Space by Means of Reaction Devices"[2] In the 1920s, Vladimir Vernadsky formulated the fundamentals of Biospherics in his book "The Biosphere," which

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offered the principle of closed material cycles on the planet Earth and the concept of an environment with huge buffers such as the atmosphere, water, etc.[3] For an active resource consumer, such as humanity, the Earth's biosphere offered a practically unlimited environment. The concept of closed cycles and matter transformation as a basis for recirculation of air, water and food in space LSS was developed further in the second half of the 20th century as a means of providing reliable long-term life support for extended space missions. During this time, several countries were engaged in a wide variety of theoretical and experimental research which confirmed that in principle this kind of operation was possible for life support. However, multiple instabilities were discovered during these tests and which put a limitation on extended system functioning and required development of countermeasures. (Please see Table 1 for more details). These tests showed that in some cases, such as the IBMP Closure Tests, IBP RAS BIOS-3 System, and Biosphere-2, microcosms and macrocosms could exist and functionally survive for years.

Table 1. CES for Human Subjects Life Support Research Historical Overview

##	Project Title	Country	Years of system operation; longest closure test	Comments: general instabilities observed
1	Earth's Biosphere	Worldwide	Earth's formation to present; this is the longest closure observed	Complex LSS for multiple bio-species: unstable space and planetary environments; species adaptation and evolution
2	BIOS – 1, 2, 3, 3M	Soviet Union/Russia (IBP RAS, Krasnoyarsk)	1965-1996; longest closure test – 0.5 year	Ecological LSS: three human subjects max, technical-engineering instabilities; unstable atmospheric composition; material deposits[4]
3	Ground Based Experimental Complex	Soviet Union/Russia (IBMP RAS, Moscow)	1963-present; longest closure test – 1 year	Physical/Chemical LSS & Social Psychological Effects of Isolation: dependence on storage materials, technical-engineering instabilities, social conflicts in a small group of human subjects[5]
7	Biosphere-2	USA	1991-1993; longest closure achieved – 2 years	Ecological LSS for a mixed gender crew of eight and multiple species were to find proper equilibrium sufficient for long-term functioning: multiple technical-engineering instabilities, Physical-chemical instabilities developed (including a drop in oxygen during the first year), unfinished ecological successions, interpersonal and intra-group conflicts.[6-7]
9	Bio/Plex	USA (JSC NASA)	1995-present; longest closure achieved – 91 days	Complex Hybrid (technical-engineering/physical-chemical/ecological) LSS: multiple technical instabilities, physical-chemical instabilities (accumulation of toxicant in the system atmosphere).[8]

10	Closed Ecology Experiment Facilities (CEEF)	Japan	2001 – present; longest closure achieved – seven days	Complex Hybrid (technical-engineering/physical-chemical/ecological) LSS: multiple technical instabilities, physical-chemical instabilities, additional closure tests are being prepared.[9]

All of these tests showed that the reducing the system buffers (such as air, water, and mineral cycles) for life support can lead to significant system instabilities. In the Biosphere-2 system, the reduction of oxygen in the atmosphere led to the opening of their hatches in order to ventilate the system. The continuous hypoxia experienced by the Biosphere-2 crew members appeared to lead to significant decrease in human performance.[10] Additionally, there were multiple instabilities observed in the BIOS-3 system including the atmospheric instability when inedible biomass was incinerated, the unstable mineral exchange due to the common use of NaCl in the food and toothpaste, and can also lead to instabilities of a more social and psychological nature by changing the size of the LSS and increasing the mission duration.[11] Please see Table 2 for a more detailed look of the history behind the Russian BIOS projects tests.

Table 2. BIOS LSS Project History Overview[12-13]

##	Project Subtitle	Years of Operation	CES Volume	Closure Quality (Net)	Comments on Human Factor (HF) issues/stresses
1	BIOS-1	1965-1968; longest closure 1-3 days	~ 12 m^3	Human-Micro/algae	Approximately 20% air recirculation; HF issues: no problems with one human subject
2	BIOS-2	1968-1972; longest closure 1-3 days	~ 20.5 m^3	Human-Micro/Algae + Higher Plants	Approximately 80 to 85% air and water recirculation; HF issues: The same as above
3	BIOS-3	1972-1991; Longest closure test 180 days	~ 315 m^3	Human-Micro/Algae + Higher Plants	Approximately 93 to 97% recirculation including air, water, and part of diet; HF issues: occasional interpersonal conflicts on the basis of age differences; no problem with machine dependence because confinement was not remote in reality.
4	BIOS-3M: BIOS-3 + Doubled Light Sources (Further Material Turnover Acceleration)	~ 1991-1996	~ 315 m^3	Higher Plants	Recirculation index as above, Some improvements of the system which supposedly led to improvements of system habitability in order to minimize human subjects stresses.
5	BIOS-3M Eco: BIOS-3 + Doubled Light Sources (Intensive CES Stability)	~ 1991-1996	~ 315 m^3	Higher Plants + Chemical Toxicants (SO_2, NH_3, Ethylene, etc.)	Further research related to more deep understanding hardware functional stability.

II. Critical Instabilities for Reduced Resources Systems

Based upon the remarks presented above, we can conclude that a reduction in the size of a life support system to that which is required for space applications will lead to multiple instabilities such as:

- Incomplete Closure/Material Recirculation which will reduce the length of closed system functioning
- Material Deposits & Removal of Elements from Circulation
- Accelerated Turnover & Instabilities
- Reduced System Physical-Chemical Buffers Effects

The comparison for some closed ecological systems is provided in the Table 3 in order to show what we are referring to when we are referring to a reduced buffers environment.

All of these instabilities, as well as additional instabilities which may appear in future closure tests, reduce the length of effective system functioning. The system inhabitants, the "bionauts," have to remain away about these potential instabilities in order to keep them under human control. This fact changes the paradigm of societal control for residents of long-term closure systems.

Table 3. BIOS LSS Project History Overview[14]

#	Parameter	BIOS-3	Biosphere-2	Earth Biosphere
1	System Volume	~ 315 m^3	> 210 * 10^3 m^3	~ 5.1*10^{18} m^3
2	System Area	~ 120 m^2	~ 1.28 * 10^4 m^2	~ 0.5*10^{15} m^2
3	Electric Power Consumption	≥ 400 kW (peak), Light	~ 6.1 * 10^3 kW, Thermal Balance (Cooling)	No electrical power, thermodynamic processes
4	System Control Principle/Stability of Operation Basis	Technological & Physiological Processes Control/Human Regulation Factor With Purpose of Self-Sustainability	Eco & Physiological Processes Statistical Regulation/Human Factor With Intention of Self-Sustainability	Eco & Physiological Processes Statistical Regulation/Human Factor as Component of Statistical Regulation
5	Energy Source for Plant Photosynthesis	Artificial Light: ~ 150 to 180 W/m^2 PAR	Natural Solar Radiation (Peak): ~ 400 W/m^2	Natural Solar Radiation (Peak): ~ 500 W/m^2
6	Crop Area (Wheat, Peas, Beets, Carrots, Cucumbers, Tomato, Potato, Etc.)	40 – 60 m^2	~ 2200 m^2	Variable and depends tremendously on growing population and available terrestrial zones
7	Plant Productivity	45 g total dry biomass per 1 m^2 daily	~ 21 g total biomass per 1 m^2 daily	Variable
8	Plant Photosynthetic Efficiency	Approximately 5 – 6 %	0.1 – 1.0 %	N/a
9	Closure Index	~ 95.7 to 97.1 %	?	~ 100%
10	Crew	2 to 3 persons	8 persons	6.1 billion
11	Time of Individual Experiments With Uninterrupted Closure	4 to 6 months	24 months	N/a
12	Bio/Technologies	Controlled cultivation of plants as an approach for atmosphere, water regeneration & food production; controlled cultivation of micro/algae for human liquid wastes utilization;	Intensive agricultural technologies without fertilizers + human labour	Depending on the level of industrial development of countries

		P/C & microbial human wastes treatment + human labour		
13	Principle of environmental control	Control from human subjects including the crew inside the system and the outside support team	Reduced control from the crew inside the system, also outside team provided environmental control	Possible statistical regulation which is possible because of unlimited environmental buffers

As it follows from Table 3, Human Active Control (HAC) is becoming critically important for long-term functional stability of the system. This approach, which could provide countermeasures of inherent system instability still has some limitations including the material limitations which have been previously considered in other investigations, the human limitations, and the stress of living in a reduced materials environment. This last two have not yet been considered in recent research.

There are three interacting blocks that need to be balanced in order to create and maintain a stable controlled ecological life support system. The first block includes the physical and material limits. Important features of this area include the interaction of material recycling and In Situ Resource Utilization (ISRU), the use of material already present at the site. These issues regarding material have been a primary concern of those studying closed systems.[15-17] Another important feature is human/machine interaction, how the crew is able to interact with the computer interface, such as via speech or handwriting recognition, in an efficient and hopefully entertaining manner in order to increase and maintain safety.[18-21]

The second interacting block is that of external stability issues. Important features of this block include the idea that a system can be completely closed to neither energy exchange nor information exchange. The inability of the CES to be closed to energy exchange is due to the Clausius Theorem and Inequality, which states that in every non-reversible reaction energy is lost.

While the first two blocks have been explored though Russian[22] and US ground based experiments[23] as well as through the International Space Station (ISS) and Mir, there have been few experiments whose primary focus is on the human factors aspect of closed systems[24] The area of human factors includes such diverse areas as physiology, individual psychology, spirituality, and social psychological group interactions including personal, sex/gender, leadership, stress, cultural, and sociological phenomena. Human factors psychology in a closed ecological system with the additional stress of reduced materials and reduced system buffers have only rarely been considered.

III. Cultural Consequences - Human Factors in Confined Environments

Homo sapiens, our species, evolved in the savannah which is a large seasonably variable grassland with few trees.[25] Many hunter-gather cultures who still live on the savannah, such as the !Kung-San Bushmen, are often studied in order to understand more how humanity may have been like prior to the development of farming. After the development of farming, cities developed long-term permanent social stratification as well as nutritional deficiencies due to reduced food diversity and higher population density.[26] This led to an overall increase in stress level as humans were forced into an unnatural arrangement so different from life on the savannah.

The basic principles of animal group interactions take several forms. In every group, there is some form of hierarchy in which certain individuals are higher than other individuals. Even amongst the most egalitarian of groups, there are certain individuals who are given more prestige than others due to difference in skills, such as having better hunting ability. Higher ranked individuals generally have better access to food sources, more mating opportunities, and other things that generally reward. The structure of many groups is fairly fluid and individuals are able to slip up and down the hierarchy. Most of this fluidity is variable across species and can be dependent on age or other factors. One of these factors and one way for an individual to rise in status would be to display aggressive behavior.

Aggression is defined by E.O. Wilson as "a physical act or threat by one individual that reduces the freedom or genetic fitness of another."[27] Wilson identified eight types of aggression: sexual, parental disciplinary, weaning, moralistic, predatory, anti-predatory, territorial, and dominance although most of these forms are not currently relevant for closed ecological systems. Aggressive behavior can quickly lead to domination of a group although it may or may not lead to becoming the most dominant animal over a long term. Not every animal may acquiesce to increased aggression, some other individuals may respond aggressively in turn preventing further dominance of the individual who first showed aggression. However, one other way for individuals to reduce the domination of the higher-ranking individual would be through cooperation and the forming of alliances. Alliances can allow several lower-ranked members to protect their resources from the higher ranking members.

Sensing an unfamiliar individual in one's territory causes the strongest aggressive response due to the possible threat that the stranger may pose. Intragroup aggression may even be put on hiatus in order to defend the group territory from strangers. This type of aggression has been seen in space crews when they are exposed to previously unknown members of the ground crew.[28]

Aggressive behavior can also be density dependent, although results for non-human primates show tremendous variation on whether the aggression and stress increased or decreased as a result of density. Although multiple papers could be written comparing all animal models and how they respond to changes in density, this paper will just mention primate models. Considering primate models and how they were stressed by density, in one study, macaques showed a decrease in male/male and male/female aggression as a result of increased density, though an increase in female/female aggression was noticed[29-30] and in another only slightly increased aggression was observed.[31] Another study using Japanese macaques showed a large increase in male aggression.[32] While the majority of studies have focused on crowding, there have also been experiments in isolation, which can also lead to excessive aggression. Again keeping with primate models, isolation caused aggression has been studied in macaques[33] as well as humans.[34]

The excessive crowding creates aggression because it interferes with the individual's *social distance*, the minimum space that an animal usually keeps between himself and another member of the same species. Not only is this dependent on the individual's species, but, in humans, it can also be based on one's culture. This study of the variation in culture's social distance is called *proxemics* and was extensively discussed by E.T. Hall[35] and reviewed by E.O. Wilson.[36] While Wilson discussed how this was common among many animals species and not just humans, Hall discussed some of the differences in how cultures view personal space. For example, the French and the Italians are able to tolerate much more cramped conditions than the Germans or the English. Further, Eastern cultures need less personal space than the Western cultures.[37]

Individual reactions to stress vary, often due to the status of the animal. Although short-term stress serves to increase aggression, long-term stress can reduce general aggression although other forms of aggression may continue.[38-40] In many species, subordinate animals are under chronic long-term stress and will tend to show more stress when dominant animals show more aggression.[41] This stress continues to accumulate over time and remains high unless social stressors can be reduced or by use of coping strategies.[42] Some of these coping strategies include handling, grooming, calling, exercise, or redirection of stress-induced aggression such as to the opponent's less aggressive kin or redirection towards a lower ranking individual in the group.[43-49] The lowest ranking individuals have no further place to displace their aggression and can suffer from any number of problems. Symptoms of excessive stress can include depression, weight loss, lack of motivation, altered risk of cardiovascular disease, and impaired learning.[50-55] In extreme cases where the individual cannot escape, the body may shut itself down in a suicidal gesture in order to escape the stress.[56]

Modern western society's life characteristics and the impact these changes have had on our physical and psychological health was reviewed extensively by E.O. Smith.[57] The advent of agriculture and domestication of animals approximately 10,000 years ago led to alterations in culture. For the first time, individuals had a regular supply of food and did not have to migrate from place to place over the year. However, because one could only tend to so many different food types, food cultivation led to a decrease in dietary diversity. Instead of being able to hunt and gather the naturally diverse food that the area provides, one had to rely on the harvest be it good or bad. This led to a decrease in overall health quality due to poor nutrition.[58-61]

In addition, the rise of agriculture allowed culture to become stratified allowing a few individuals to provide for the whole group. The non-farmers were able to increase their population density by moving into higher density towns and small cities. These individuals, free from being responsible to search for their own food, were able to specialize and hierarchy became more permanent. The increased population density decreased personal space, increased stress and, when combined with being in close contact with other humans and their waste products, further reduced health.[62]

Eventually, the increased technology that was developed started to further increase stress. Certain aspects of technology, such as the overdependence on cars or horses, allowed decreased physical exertion leading to a decrease in physical and psychological health. Technology has allowed for a tremendous increase in mobility, which has allowed a wider dispersal of individuals and increased *neolocal* accommodations. Neolocal families are far from extended family leading to a decrease in a familial support system, which was present for most of our heritage. Increased workload, increased demands on time, and decreased social support lead to increased chronic stress and increased aggressiveness.

As a closed system is dependent only on itself for survival, the crewmembers have a more unique and more stressful life than a more traditional open system. While a decrease in dietary diversity has lead to decreased overall health in the past, only a small portion of our modern diet is being researched for use in the space program likely leading to further deterioration of health.[63] Being in an enclosed environment has also led to psychological instability and acute mental stress, as several experiments in polar psychology have shown.[64-65]

Stress and its effect on health are also increased due to increased isolation, decreased ability to escape, increased responsibility for the CES, and decreased privacy and personal space.[66-69] Increased stress has led to psychological incidents including increased aggression, disturbing fantasies, anxiety, depression, hallucinations, near loss of a crewmember, and withdrawing from the group.[70-71] These psychological incidences if severe enough could result in loss of the craft or crew. For more information, please see Reference 72.

IV. Conclusion

Artificial life support systems, which mimic the Earth's Biosphere, all are significantly reduced in their functional stability. This stability reduction extends from the physical and chemical instabilities to *socio-psychological instabilities of long-term confinement with reduced life support resources.* The only way to increase the stability of a closed environment is through a Human Intelligent Control Approach, which is a relatively new term requiring further definitions. Generally, this approach means we can no longer continue our interaction with environment based on unlimited consumption as we do today. This interaction has to be replaced by balancing consumption and re-circulating the wastes back into consumable resources. And the *rate of recirculation* has to be no higher than some natural environmental stability limit, such as that determined above. We need to replace the above formulated principle of Human-Environment Interaction based on unlimited consumption philosophy, with the relatively new principle of self-sustainable system functioning and operations which in a closed ecological system, is contradictory to the principle of unlimited consumption. This provides a motivational challenge to the crew operating in a reduced resources environment and requires a mental reconstruction and change in the way of thinking. This change, which has applications far beyond a closed system for life support, cannot happen unless we start practicing for sustainable functioning in a reduced resources environments with the subsequent development of new social (and mental) standards in order to continue to "live well" by the standards of one's culture. All of this, plus the multiple physiological and psychological stresses will require a higher level of training for crew members involved in long-duration voyage toward remote planets. Centralized experimental works are required (such as experiments with the "Biosphere-2" system) to develop optimal practices for the functioning and operation of such systems. Recommendations for long term survival in small size closed environments could also be suggested, such as a more rigorous approach to researching of human factors in confined remote settings, more extensive training for crew members of long-term confined missions, and more accurate approach to resource balancing in confinements, including human socio-psychological resources.

Some future directions for this work include long-term confinement in the prison system which maybe an adequate simulation for long-term space mission such as mission to Mars. Additionally, more tests such as "Biosphere-2" or similar analogous tests would continue to be appropriate for Human Factors research. The Russian Space Agency, in close collaboration with the European Space Agency and other interested parties, is currently preparing a 500 to 700 day closure test with a partial purpose of modeling human factors stability issues in a small group of six to eight test subjects in confinements which will simulate a mission to Mars and back.

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