Cluster 4: Habitat Management - Report

CLUSTER 4
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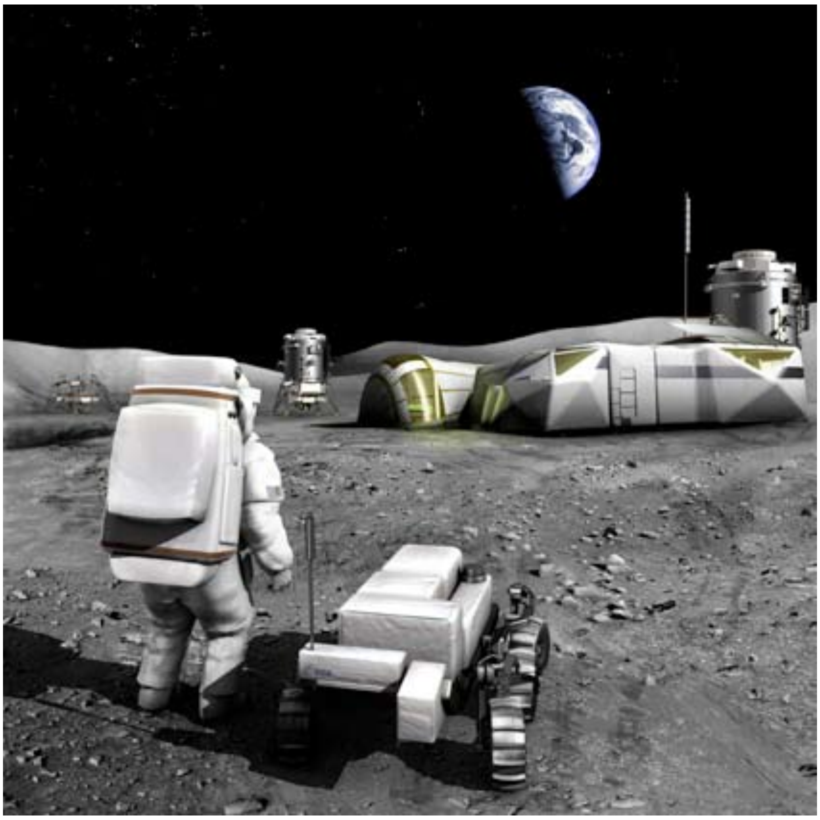
Towards Human Exploration of Space: a EUropean Strategy



Cluster 4: Habitat Management - Report

Microbiological Quality Control of the Indoor Environment in Space

Life Support: Management and Regeneration of Air, Water and Food

THESEUS: Towards Human Exploration of Space – a European Strategy

Past space missions in low Earth orbit have demonstrated that human beings can survive and work in space for long durations. However, there are pending technological, medical and psychological issues that must be solved before adventuring into longer-duration space missions (e.g. protection against ionizing radiation, psychological issues, behaviour and performance, prevention of bone loss, etc.). Furthermore, technological breakthroughs, e.g. in life support systems and recycling technologies, are required to reduce the cost of future expeditions to acceptable levels. Solving these issues will require scientific and technological breakthroughs in clinical and industrial applications, many of which will have relevance to health issues on Earth as well.

Despite existing ESA and NASA studies or roadmaps, Europe still lacks a roadmap for human exploration of space approved by the European scientific and industrial communities. The objective of THESEUS is to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non-space applications and dual research and development.

THESEUS Expert Groups

The basis of this activity is the coordination of 14 disciplinary Expert Groups (EGs) composed of key European and international experts in their field. Particular attention has been given to ensure that complementary expertise is gathered in the EGs.

EGs are clustered according to their focus:

Cluster 1: Integrated Systems Physiology
Bone and muscle
Heart, lungs and kidneys
Immunology
Neurophysiology
Nutrition and metabolism

Cluster 2: Psychology and Human-machine Systems
Group/team processes
Human/machine interface
Skill maintenance

Cluster 3: Space Radiation
Radiation effects on humans
Radiation dosimetry

Cluster 4: Habitat Management
Microbiological quality control of the indoor environment in space
Life support: management and regeneration of air, water and food

Cluster 5: Health Care
Space medicine
Medication in space

Identification of Research Priorities and Development of the THESEUS Roadmap

Each Expert Group based their work on brainstorming sessions dedicated to identifying key issues in their specific field of knowledge. Key issues can be defined as disciplinary topics representing challenges for human space exploration, requiring further attention in the future. These key issues were addressed to the scientific community through an online consultation; comments and inputs received were used to refine them, to consider knowledge gaps and research needs associated to them, as well as to suggest potential investigations.

The outcomes and main findings of the 'Integrated Systems Physiology' EGs have been synthesised into this report and further integrated to create the THESEUS roadmap.

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1 Introduction to Habitat Management in Space

Despite the many benefits of using robots to explore the universe, the ultimate goal and attraction remains in human beings discovering and experiencing space. The habitat (spaceship or space station) that will house future space travellers plays a crucial role in making any space endeavour a success (Nicogossian et al. 1992).

Humans in space need a habitat that provides:

- protection from environmental hazards (e.g. objects, pressure, temperature, radiation),
- supplies and consumables to survive (air, water, food),
- removal and stabilisation of waste in order to ensure maximum mass recycling.

The habitat should contain systems to assure:

- control of the indoor environment (quality of air, water, food, surfaces, waste),
- production or regeneration of air, water and food,
- removal and treatment of waste for recycling and stabilisation of irrecoverable fraction.

In all systems, microbes play an important role and should be controlled if harmful or used for the benefit of the mission to the maximum extent possible.

In this context, two themes related to habitat management in space were identified and taken into account within the scope of the THESEUS project:

- Microbiological quality control of the indoor environment in Space
- Life support: management and regeneration of air, water and food

The priorities of research necessary to support foreseen space travel and planetary exploration represent a unique set of problems whose solutions demand an in-depth understanding of the whole human body and cross-disciplinary work between life scientists, engineers and technologists. All the necessary expertise was been acquired by European scientists during the past decades. In the context of the THESEUS project, the objective of the expert cluster on 'Habitat Management in Space' was to gather this European expertise and create synergies that allow for an integrated approach on which priorities of research emerge. Because of the necessary holistic approach, those research programmes obviously required the involvement of scientists whose expertise is disseminated across Europe.

2 Microbiological Quality Control of the Indoor Environment in Space

2.1. Introduction

The subsequent sections present the recommendations from the Expert Group focused on 'microbiological quality control of the indoor environment in space' as well as the rationales behind them. In this context, the group focused on indoor environmental quality control and thus environmental microbiology in space in order to reduce potential hazards for the crew and the infrastructure, including:

- health hazards of microbial origin, including human exposure to e.g. pathogens, antigens, allergens, toxins, volatile organics,
- infrastructure hazards of microbial origin, including e.g. biofilm development on surfaces, biocorrosion of metal surfaces, and biodegradation of polymers surfaces.

The subject of monitoring and understanding the behaviour of 'the human microbiology' (e.g. dental, skin, intestinal, vaginal microflora) in space was not considered as a priority topic here, as it was already emphasised by the THESEUS Immunology and Nutrition/Metabolism Expert Groups.

Nevertheless, it has to be emphasised that the human microbiome plays a key role in the health (e.g. digestion) of the astronauts in space and is in fact the major source of environmental microbial load in space habitats.

In addition to microbiological contamination, it was recognised that chemical compounds (e.g. trace gasses in the air including volatile organics such as ethylene, formaldehyde, iodine or silver in water) also contribute to the indoor environmental quality. The importance of particles (e.g. dust) on environmental quality is also highlighted, as particles are considered to be major carriers of microbial contamination. Even when not posing a direct risk for crew, some chemicals and dust may interfere with hardware or scientific investigations inside the habitat, and thus should be controlled. However, no specific recommendations on these topics are formulated in this report.

Furthermore, monitoring the external environment (e.g. lunar dust) and its impact on the indoor quality control in lunar, Martian or asteroid surface habitats should also be taken into account, but is not discussed in this report.

The following sections present the key issues identified by the 'microbiological quality control of the indoor environment in space' Expert Group. This group met during two expert workshops in 2010. These workshops were organised sessions, aimed at considering the key questions to address the latest developments, gaps to fill and Earth-based applications.

2.2. Microbiological Quality Control of the Indoor Environment in Space – Key Issues

2.2.1. Key Issue 1: Define correct upper and lower thresholds for indoor environmental quality control of air, water, food and surfaces in space habitats

Relevance for space exploration

Setting correct thresholds for microbial control in space vehicles becomes increasingly important for longer duration missions. This importance is linked to the intrinsic semi-closed loop characteristics of air and water supply in space vehicles that may amplify and enhance microbial contaminations. In respect to human risk, the importance is lower for a LEO (ISS) mission as crew fast return is possible, compared to a long duration mission to Mars where fast return is no longer possible. However in respect to economics, the importance is not negligible in LEO missions as up and down load of replacement hardware and water supplies that were lost due to contamination is expensive.

Terrestrial interest and application

Defining upper and lower thresholds for indoor environmental quality control that correctly reflect beneficial or harmful impacts of environmental contaminants and pollutants is of importance on Earth for assuring healthy housing and working areas (e.g. allergies, sick building syndrome, etc.), preventing nosocomial infections (e.g. in hospitals) and for the ecotoxicology field (e.g. exposures to low pollutant concentrations in water or air). However, experience and expertise has been build up over the years for controlled inhabited environments on Earth, and adequate thresholds have been defined. Therefore, additional information from space would mainly be useful to further optimise or adapt thresholds that are already in place for certain Earth environments.

Figure 1: NASA astronaut Dan Burbank cleans cabin air bacteria filters in the Tranquillity node of the ISS (Credit: NASA)

On Earth, limits are set for many chemical and biological agents present in indoor environments (e.g. WHO, 2000) and workplaces. Most occupational limits are given for short term exposure (15 min to 8 hours per day) and are usually based on irritation or other short-term harmful properties of the agents.

Background and European Strengths

In space vehicles, exposures are continuous (24 hours per day, for months or even years). In addition, the immune status of astronauts in space is compromised due to stressors (radiation, microgravity, isolation) (Sonnerfeld, 2005; Williams et al., 2009) and microbes may change behaviour (e.g. become more pathogenic) (Wilson et al., 2007), thus special thresholds may be required for space habitats.

Currently, standards and thresholds are internationally agreed upon for the working and living modules of the International Space Station (MORD, 2009). However, no/different thresholds are set for the cargo modules travelling to the station (e.g. the MORD document is not applicable for ATV). They are defined as maximum allowed concentrations (MAC) of fungi and bacteria, in air, potable and hygienic water, and surfaces (MORD, 2009), and are defined in viable and agar cultivable cell numbers. Other microbial environmental contaminants (such as fungal allergens, viruses, protozoa, amoebae, mites, etc.), which could be equally important sources of infection, allergies, or material destruction, are not listed. The current thresholds for the ISS are very conservative and generally lower than applicable on Earth (i.e. only low levels of microbes are allowed). Most of the time, the thresholds are defined on concentrations which are technically achievable for prevention or detection, but lack often a medical or infrastructural hazard basis.

Nevertheless, microbial induced structural damages on the ISS have been observed and reported (fungal biofilms on air exposed metal and polymeric surfaces, bacterial water contamination, etc.) (Novikova et al. 2006). This infrastructural damage will become even more of a risk for longer missions when routine replacement of parts is no longer feasible and more intense regeneration of air, water and waste into food is required. It is true, however, that with the current thresholds implemented on the ISS, very few medical incidents are reported (not published). Then again, questions can be posed on if severe reduction of microbial levels (in food for instance) does not pose a risk in itself, as the human body needs microbes (Jermy, 2010).

Many European institutes have microbiological research groups that have performed valuable work to evaluate the health hazards of agents present in indoor environments. Guideline or threshold limits have been set for harmful chemicals and some microbes for given environments (e.g. hospitals), and are correctly based on combination of toxicological and epidemiological studies.

Proposed investigations and recommendations

- Define the list of microbes and their thresholds (maximum allowed levels) to be controlled before flight in the crew habitat.
- Define thresholds primarily based on scientific data and mathematical models as basis for correct assessment of risk for crew and infrastructure, and then secondary evaluated these thresholds versus the technological achievable detection limits
- Define thresholds taking into account potential 'essential/ beneficial' effects of microbial compounds (e.g. trigger and keep active the immune system, enhance natural protective microbial barrier)
- Define thresholds at an integrated level, taking into account the combined (synergistic or antagonist) effects and risk assessment of exposure of crew and infrastructure to:
    - multiple contaminants of microbial origin, including e.g. viruses, bacteria, yeasts, fungi, amoebae, ciliates and other protozoa, dust mites, exo- and endo-toxins, mycotoxins.
    - multiple sources including e.g. air, water, food, surfaces, waste, other crew members.
    - multiple stress factors including, e.g. microbial contamination and others such as chemical and dust contamination, radiation and gravity.

- Use in priority ISS as a validation platform (e.g. are thresholds achievable under daily operations in space stations) for thresholds in space habitat settings, and secondary use relevant Earth analogues such as remote and confined locations that require long-term habitation without access to outdoors (e.g. Mars500, Concordia, submarines/submersibles, Antarctic/Arctic stations, hospitals, clean rooms)

2.2.2. Key Issue 2: Develop efficient materials and methods to prevent environmental microbial contamination in space

Relevance for space exploration

In respect to human risk, the importance of prevention procedures is lower if fast crew return is possible, but becomes more important in long-duration missions.

In respect to economics, the importance of prevention procedures is high, as significant are possible due to up and down load of replacement hardware and water supplies that are lost for consumption due to contamination.

Figure 2: The Herschel spacecraft in a clean room at ESA ESTEC (Credit: ESA)

Terrestrial interest and application

On Earth, efficient mitigation procedures are mostly in place. Additional terrestrial interest may lie in the health sector (e.g. improving indoor air quality in public buildings such as hospitals, schools, and public transport), or in the artistic and cultural sector for the preservation of art or historic buildings. There is also a strong interest for industry using clean room production facilities such as in pharmacies, and electronics or food preparation and packaging. For food and pharmaceutical industry, such methods and materials are of interest to prevent spoilage and increase shelf life of products. Novel multifunctional materials including, for example, antimicrobial coatings (silver nanoparticles, biosurfactants, etc.) or novel (non-volatile) biocides are also of industrial interest for a wide variety of industrial applications.

Background and European strengths

A large scientific and industrial community exists that deals with prevention of microbial contamination (e.g. work in clean rooms) and air, water, food and surface preservation. However, this knowledge and technology is not always directly transferable or applicable for the specific materials and environmental conditions in space.

In most spacecraft assembly rooms, there is a control of the total particle burden (e.g. through air filtration and protective clothing of personnel) in an effort to indirectly control the particle-linked bioburden (Victoria et al., 2006; Warmflash et al., 2007). Additionally, surface sterilisation methods are sometimes used such as UV light irradiation or disinfection with chemicals.

However, history shows that these strict quarantine procedures were not effective in preventing contamination of some spacecraft (Schuerger, 1998). Microbial contamination studies in spacecraft over the last 30 years indicate that a high diversity of bacteria, fungi, and Actinomycetes are commonly carried on-board, most likely via clothing, equipment, air currents during spacecraft handling and loading, food, and the astronauts themselves (Novikova et al., 2006). It has been demonstrated that microbial contamination in confined manned habitats is primarily originating from human and human activities (Van Houdt et al., 2009).

A large industry exists in Europe dealing with air, water, food and surface quality assurance, for occupational health, food and pharmaceutical industry, antifouling in the marine field, and biosafety laboratories. Space research could benefit from the current and on-going developments on Earth in these sectors without having to develop independent R&D strategies. However, the existing technologies are not always directly transferable or applicable for the specific materials and environmental conditions in space, and thus adaptations will be required.

Proposed investigations and recommendations

- Apply better facility design that allows preventing contamination (e.g. smooth edges, no corners, use of HACCP analysis).
- Define the list of microbes (e.g. latent viruses, opportunistic pathogens) that should be confirmed as absent in the crew before flight, as crew will be the major source of the microbes dispersed in the environment.
- Develop efficient maintenance systems for prevention of microbial dispersion through air (e.g. air filtration, adsorption processes) that are continuous, autonomous, compact in size and weight, long-lasting, compatible with space materials, not using toxic or flammable chemicals and with low requirements for energy, consumables and maintenance.
- Develop efficient materials that prevent microbial adherence, proliferation and biofilm formation on surfaces, and metal biocorrosion and polymer biodegradation (e.g. antimicrobial nanostructures or coatings, silver nanoparticles, biosurfactants)
- Develop novel biocides (non-toxic for the crew, e.g. bacteriocines) and/or alternative measures to control microflora (e.g. physical) to apply in air and surfaces or water and food.
- Develop systems and procedures to prevent water and food spoilage during in-situ production or storage. Quality control of water and food, in specific, will become more important when water and food will be in-situ produced, prepared, and stored ('fresh') during long term missions.
- Develop Prophylactic measures to fend off a disease or another unwanted consequence such as crew dysmicrobiosis or infection, for example by suppression of harmful agents via competition with beneficial agents on skin or mucous tissues, by use of pre- and probiotics or fermented food products to prevent impact of consumption of sterilised food over prolonged periods on intestinal microflora and digestion, by strengthening e.g. the colonial resistance and prevention of vaginal bacteriosis.
- Evaluate the efficiency of prevention design and maintenance procedures in space (e.g.in ISS, under standard upload or crew operations) or relevant analogues on Earth.
- Develop models describing the contamination kinetics in a closed system, including multiple microbial species in competition and possible sinks of contamination, in order to predict and control contamination.

2.2.3. Key Issue 3: Develop adequate environmental contamination monitoring (prediction, detection, identification) systems for use in space

Relevance for space exploration

In respect to human risk, the importance of monitoring is lower when fast crew return in possible, but very

important for long-duration missions.
In respect to economics, the importance is high as significant losses are linked to up and down load of for replacement hardware and water supplies that were lost for consumption due to contamination.

Terrestrial interest and application

The development of early detection and warning systems for environmental contamination and pollution is of common interest for space and on Earth. Such autonomous systems could be used to assure healthy environments in housing and working buildings, in hospitals for fast screening of incoming patients (carrier state), emergency situations, for the prevention of nosocomial infections in public areas and public transport, and in pandemic control in case of natural catastrophes. Potential medical applications are ample, including on-site infection detection and identification, and diagnosis. In addition, such systems will be of interest for continuous quality monitoring of air, water, surfaces and products in production facilities for the food and pharmaceutical industries.

Background and European strengths

Despite effective contamination prevention measures, data shows the successful colonisation of space station environments by microbes (Novikova et al, 2006). It has been demonstrated that microbial contamination in confined, manned habitats is primarily originating from humans and human activities (Van Houdt et al., 2009). Harmful microorganisms emerge naturally, even in the absence of indigenous hosts, and are able to adapt to and become dominant in closed spaceships or stations (Warmflash et al. 2007; Bernasconi et al., 2010).

Thus, such fluctuations in microbial concentrations and trends in contamination events suggest the need for continued diligence in monitoring and evaluation, as well as further improvements in engineering systems (Castro et al. 2006). The knowledge obtained from microbial control during past missions is critical in driving the design of future spacecraft monitoring systems.

Over the last decade, rapid developments have been made in molecular biology and genetics using high throughput cellular and molecular analysis systems (e.g. microfluidics devices) coupled with bioinformatics that allow 'de novo' detection (without prior sequence knowledge) of DNA sequences, proteins or lipids etc. This could help the development of fast, on-line detection systems (Sakamoto et al., 2007; Stîngu et al., 2008; Fricke et al. 2009). Unfortunately, these systems are currently large in size, require many consumables and operator interventions, and will need to be redesigned for any future space application.

Europe is rich in scientific and industrial communities dealing with environmental hygiene in hospital and industry. Also valuable expertise in risk assessment exists in many European countries.

Proposed investigations and recommendations

- Develop a due point monitoring system (sensors to most critical niches)
- Develop adequate sample collection procedures and mobile sampling systems, exploiting novel collection techniques and materials (e.g. filtration, adhesion, absorbents, electrostatic attraction, etc.), that allow to correctly assess the microbial contamination on multiple locations in the habitat
- Develop sample analysis systems that
    - are rapid (real-time), on board, compact, automated, sensitive (detect low concentrations), allow quantification and identification, not using toxic or flammable chemicals and with low requirements for energy, consumables and maintenance.
    - deliver in priority a rapid total contamination assessment (total microbial burden), and in a second (potentially slower) step a more detailed identification and quantification of the specific components of the contamination.
    - detect also the 'in advance unknown' (new arising) microorganisms or events
    - detect, in addition to the presence and quantity, also the 'activity', of the microbial population
- Develop sampling and analysis systems that allow simultaneous monitoring of multiple microbial contaminants, including viruses, bacteria, yeasts, fungi, amoebae, ciliates and other protozoa, dust

mites, exo- and endo-toxins, mycotoxins, volatile organic compounds, etc.

- Develop sampling and analysis systems that are preferentially applicable to multiple sources, including air (in priority), air cleaning systems (e.g. filters, heating/drying coils), water, surfaces, food, waste, and/or crew (e.g. dental, skin or intestinal microflora, breath chemical composition, as markers for crew health). Microbial quality control of water and food, in specific, will become more important when water and food will be in-situ produced, prepared, and stored during long term missions.
- Develop an ad hoc statistical model based approach for predicting colonisation hotspots and optimising sampling procedure

2.2.4. Key Issue 4: Develop materials and methods to mitigate environmental microbial contamination and its harmful effects in space

Relevance for space exploration

In respect to human risk, this research priority might be lower for LEO missions as fast crew return in possible, but will become more important for long term missions where fast return is no longer possible. In respect to economic development and implementation of decontamination procedures, this topic is important for both short and long term missions, as even in short term missions significant losses are encountered due to up and down load of replacement hardware and water supplies that were lost for consumption due to contamination.

Terrestrial interest and application

Development of microbial decontamination procedures for space will be of interest for water quality control on Earth, hospital management, the food production and processing industry (cleaning technology and hygiene control), and the material industry (self-cleaning surfaces or easily cleanable surfaces).

Background and European strengths

Precautionary measures can keep the presence and abundance of many medically and/or technologically significant microorganisms low during a space mission. Nevertheless, microbial proliferation in the environment causing infection of crewmembers and harmful effects on the cabin may still occur. Adverse effects of microbes on technological equipment and cabin have been reported (Novikova et al., 2006) and some effects were potentially life threatening for the crew (Novikova, 1999). Because of such cases, adequate systems and procedures to deal with the problem (including emergency response and corrective actions) have to be in place. Thus, it is necessary to determine the efficacy of current mitigation strategies and countermeasures for long term space missions and if needed, to formulate additional recommendations for operational remedies to cure harmful microbial contamination events.

A large scientific and industrial community exists in Europe which is dealing with air, water, food and surface decontamination (e.g. sterilisation procedures in food industry, in hospitals, in pharmaceutical industry). However, existing technologies are not always directly transferable or applicable for the specific materials and environmental conditions in space.

Proposed investigations and recommendations

- Apply better facility designs that allow easy decontamination (e.g. smooth edges, no corners, use of HACCP analysis, etc.)
- Develop contamination mitigation products or systems that are highly efficient, rapid, compact, compatible with space materials, not using toxic or flammable chemicals and with low requirements for energy, consumables and maintenance.
- Develop contamination alleviation procedures that are preferentially applicable to samples from multiple sources, including air (primarily), water, surfaces, food, waste, and/or crew.
- Develop contamination alleviation procedures for food and water decontamination. Quality control of water and food, in specific, will become more important when water and food will be in-situ ('fresh') produced, prepared, and stored during long term missions.
- Develop contamination mitigation procedures that allow removal of microbial biofilms from surfaces (e.g. non-volatile biocides, electrical

currents, radiation including UV, etc.), stop metal biocorrosion, and polymer biodegradation.

- Develop contamination mitigation procedures that allow treatment and curing of human dysmicrobism (an imbalance of the normal flora) and infections, e.g. via modulation the human microflora by use of pre- and probiotics or fermented food products.

Figure 3: An example of microbial contamination that developed on an interior panel aboard the ISS. Attempts to clean the panel with supplies aboard the ISS failed and the panel and to be replaced. (Credit: NASA, image ISS010E11563)

2.2.5. Key Issue 5: Acquire better knowledge on microbial community (microbial ecosystem) dynamics and microbial cell evolution over time in confined manned habitats in space

Relevance for space exploration

In respect to human risk, the importance of inflight decontamination is lower when fast crew return in possible, but very important for long-duration missions.

In respect to economics, the importance is high as significant losses are linked to up and down load of replacement hardware and water supplies that were lost for consumption due to contamination.

Terrestrial interest and application

In space vehicles, only a 'simplified' microbial community is able to develop (only source is the humans, without interaction with plants, soil, animals). Space research could give a better understanding of microbial community dynamics under environmental conditions, which could be of interest for more complex Earth communities. A better knowledge and database of indicator organisms for expected/dominant microbial populations in confined habitats is also relevant for indoor environmental air quality in housing and living buildings on Earth in general, or for specific applications such as treatment of immune-depressed patients in hospital. A better insight into the processes of acquisition and selection of resistances to antibiotics and biocides is also highly valuable for the medical sector. Intestinal microbiota are likely involved in many disease states, and understanding not only how these bacteria are influenced by environmental parameter, but also how to modify the microbiota to effectively reduce these diseases are highly needed.

Background and European strengths

Because microbial contamination of spacecraft cannot be avoided, research must be initiated to better understand how microorganisms and microbial communities evolve and interact with humans, animals, plants and materials in space environments (Gu et al. 2007, Castro et al., 2006). For example, the influence of reduced microgravity, reduced gas or liquid convection and settling of particles, higher doses of radiation, and lower pressure and oxygen concentration in space on microbial distribution and development in space habitats is not known. The fast developments in molecular biology and genetics using high throughput cellular and molecular analysis systems (e.g. –omics tools for genome, proteome, metabolome, profiling, microfluidics analysis devices) coupled to bioinformatics allow 'de novo' detection (without prior sequence knowledge) of DNA sequences, proteins or lipids etc., for microbial community and activity analysis could help to significantly improve our knowledge (Sakamoto et al., 2007; Fricke et al. 2009).

The community of environmental microbiologists in Europe is very active, with many teams of world importance. Specialties include human microbial ecology (intestine, skin, etc.), animal microbial ecology (rumen cow, etc.), plant microbial ecology (root, leaves, etc.), soil bacterial ecology, water microbiology, microbial genetics (Mobile Genetic Element), biotechnology industry etc.

Proposed investigations and recommendations

- Collect new data on microbial community dynamics and microbial cell evolution in confined habitats in space (e.g. ISS) or analogues on Earth under space relevant conditions, by sampling and analysis, and by building a shared database (i.e. of sequences and physiological, biochemical, ecological data, etc.) and a shared space microbial culture collection.
- Identify and describe the role of environmental parameters (temperature, humidity, confinement, increased radiation, reduced gravity, reduced pressure, modified chemical composition of the atmosphere, growth substrates) for induction or selection of changes in microbial communities and cells over time in air (in priority), water, surfaces, food, waste, and human microflora communities (e.g. identify favourable conditions and niches).
- Identify and describe the processes involved in changes in microbial abundance, diversity, interaction (including gene transfer), and microbial ecosystem equilibrium; genetic evolution over multiple generations (mutation rates by natural replication errors or mobile genetic elements, and induction and selection processes), evolution of chromosome length and gene expression (e.g. activation of pathogenicity), evolution of cell proliferation rates, surface attachment and colonisation etc.
- Identify key microbial players and representative early indicators (e.g. certain bacterial species, or even bacterial phages) and markers for microbial presences and activity that can be used in monitoring systems for air (primarily), water, surfaces, food, waste, and human microflora communities (human microbiome) (e.g. dental, skin, intestinal, vaginal microflora).
- Investigate the evolution of model microbial communities under space conditions (e.g. long-term space flight experiments). The ISS would be an excellent platform for long-term evolution experiments using in-situidentified microbes.
- Develop mathematical models based on a comprehensive understanding of the underlying phenomena for explaining and use them for better global management (prediction, control and modulation) of microbial community evolution.

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3 Life Support: Management and Regeneration of Air, Water and Food

3.1. Introduction

The subsequent sections present the recommendations issued from the Expert Group focused on 'Life Support: Management and Regeneration of Air, Water and Food' as well as the rationales behind them.

The group's interest covers life support for self-sustainability via regenerative processes using physical, chemical and biological technologies. This includes:

- air revitalisation (CO2 removal & O2 production),
- water supply and recycling,
- food supply (plants, microbial),
- waste management (removal & recycling).

Whenever human beings live and work in a confined habitat over extended periods of time, it is the task of the life support system to achieve and maintain a physiologically acceptable environment within the habitat. An efficient environmental control and life support system (ECLSS) essentially takes charge of two complementary functions in a balanced and controlled manner: (i) it provides the input resources required for humans and other biological species in the habitat, and (ii) it processes human and other outputs and waste.

The requirements of life support systems change drastically when humans are subjected to exploration type missions facing interplanetary and planetary environments. Different issues have to be considered for the transfer phases from Earth to the Moon or Mars, and back, and for the stay on the surface of the celestial body. Thus far, available life support techniques are based almost entirely on physical-chemical processes. Long-term and repeated exploration missions however demand for alternative methods, including (i) biological processes for food production mimicking natural processes of the Earth's biosphere, and (ii) the use of natural resources available on extra-terrestrial bodies. The basic reasoning behind this is that human beings cannot survive in the absence of organic

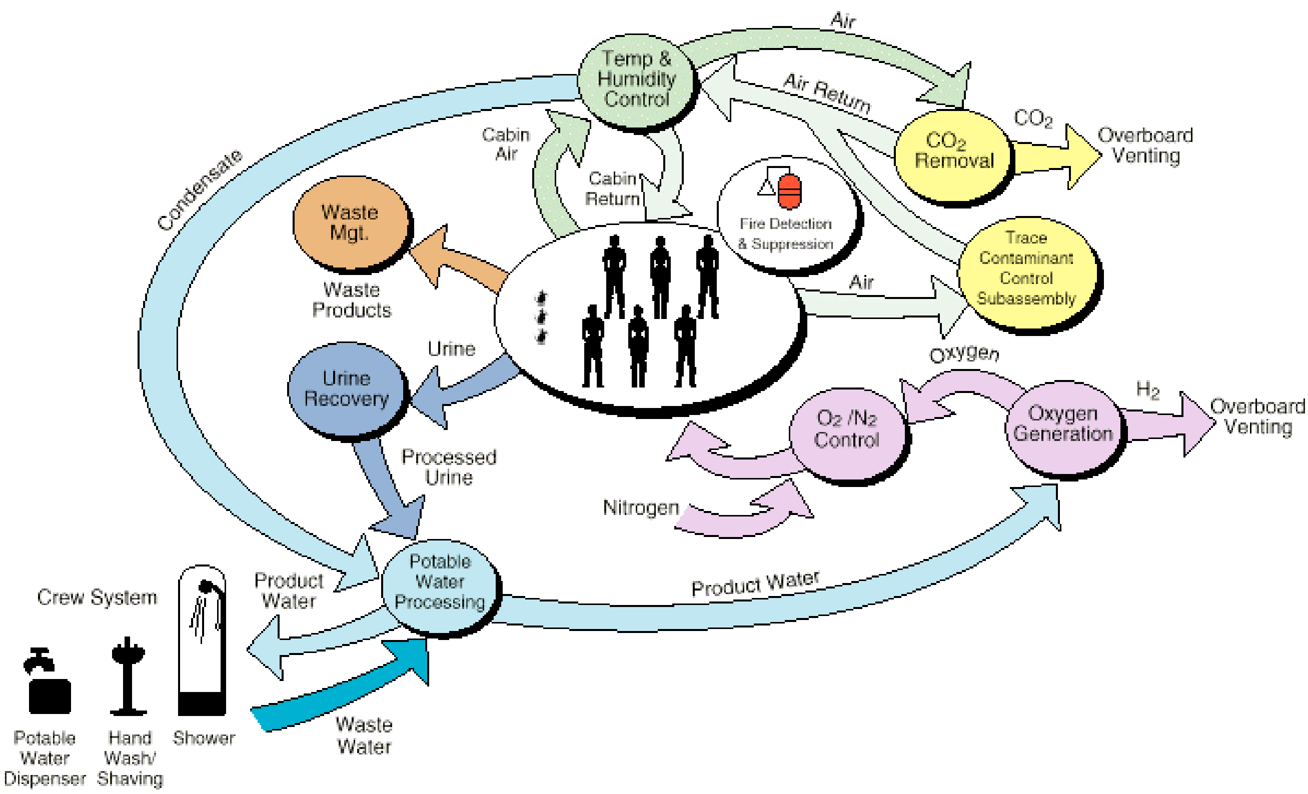

Figure 4: The current baseline for the ISS ECLSS system (Credit: NASA)

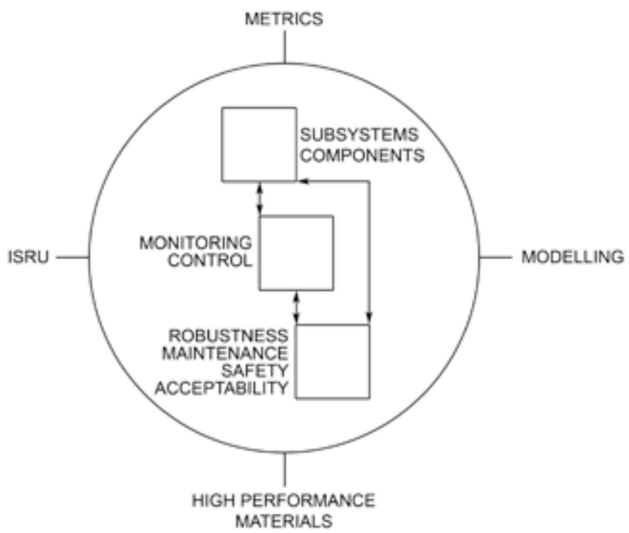

Figure 5: Steps necessary for life support system development

life, making food production a primary issue. This must be linked to other life support functions as well, such as water and waste recycling. In turn, this calls for an integrated vision and approach to studies of life support technologies using intertwined biological, physical and chemical processes.

A key driver in the design (and ultimately selection) of life support processes for human space exploration is the need to minimise the use of consumables. This is important because of the tremendous costs associated with transporting mass to space. In general, the issues are related to safety, reliability, microgravity operation, attention to consumables and waste products, complexity of closed systems, simplicity in operation, maintenance, repair and control, materials selection, human factors and interfaces, level of maturity and uncertainty, minimisation of consumables, scale of design and operation, mass system, and integration with other operations.

This involves a broad variety of subjects and levels, from material science to system level evaluation, each needing attention and research. The Expert Group has chosen to classify the different topics following a hierarchical logic, from global aspects (metrics development; system level studies) to specific issues (subsystems improvement and development) and transverse issues (material science, modelling issues) (Figure 1).

It was also recognised that life support system design and implementation should be part of an overall sustainable and ergonomic habitat design, i.e. implementing resource and energy efficient buildings, sustainable construction practices, healthy and productive indoor environment, as well as energy-efficient housing and working. Thus, architectural and psychological aspects will also have to be taken into account when considering life support systems. It is well established and acknowledged that this point is a policy implementation issue, not a research priority.

The following sections report the conclusions the 'life support: management and regeneration of air, water and food' Expert Group. This group met during two expert workshops in 2010. Those workshops were organised sessions aimed at considering the key questions to address, the latest developments, the gaps to fill and the earth-based applications.

3.2. Life Support: Management and Regeneration of Air, Water and Food – Key Issues

3.2.1. Key Issue 1: Develop and adopt common metrics for evaluation of different Life Support System (LSS) architectures, technologies, and their evolution

Background and European strengths

The life support system is a major, multipurpose matter for human exploration. Currently, different metrics are used by different space agencies. While the NASA equivalent system-mass (ESM) approach is still the baseline (BVAD), it is now considered to be too narrow. There is a need for an independent selection procedure to evaluate LSS solutions in order to provide inputs to the CDF (Concurrent Design Facility) database. The approach of this evaluation and selection is a difficult trade-off between technical, safety, cost and strategic considerations. For any LSS project, it would be necessary to take a multi-criteria approach, including emerging criteria, due to the fact that LSS is an integration of systems or subsystems.

The integrated methods and tools must:

- evaluate global LSS behaviour in closed loop,
- assess and score safety & reliability,
- take into account all its enabling logistics.

There are important trends and European strengths (University of Lausanne) for managing the transition from today's unsustainable arrangements to more sustainable projects (Erkman, 2003). This is the subject of eco-restructuring and industrial transformation. These topics are strictly linked to new bodies of economic and political theory and practice and are highly dependent on system evaluation methods. This is the core of research and developments regarding common metrics for evaluation of different Life Support System architectures, and technologies. Industrial ecology is central to these fields with an emerging body on theory, tools and practices.

The International Society for Industrial Ecology seeks to build a community of interest, support cumulative learning, produce quality research, and promote social change.

Proposed investigations and recommendations

- due to the fact that LSS is an integration of systems or subsystems, consider dynamic and flexible approaches that can integrate new emerging criteria.
- develop a LSS system model and a support toolbox evaluator firstly working with some a priori significant criteria.
- deploy an overall simulator and use ALISSE - Advanced Life Support System Evaluator - for actual case studies (Brunet, 2009).
- deploy standards for collecting, validating and making available the data for system evaluation and multi-criteria optimisation.
- evaluations of operational results from LSS with ALISSE

Terrestrial interest and application

Today, the major studies on environment issues and sustainability, e.g. in the field of industrial ecology, mainly focus on one requirement at a time (energy consumption, water consumption or any other). However, there is a need to approach systems with a much more integrated view, taking multiple requirements into account. Although the key criteria are may be not the same for space and Earth applications, the methodology and metrics used for space certainly could be valuable for Earth-based systems as well. As LSS complexity (required variety) is currently not known precisely, assessment methods and tooling will surely evolve. Assessment needs and methods have to have a simultaneous and continuous approach with LSS development and increasing level of complexity. This completely matches with the methods of integrating environmental concerns in industrial developments by finding innovative solutions to complicated environmental problems, as in the emerging domain of industrial ecology (Erkman, 2003).

3.2.2. Key Issue 2: Develop model-based regenerative Life Support via a system level approach

Background and European strengths

Figure 5: NASA astronaut Jeffrey Williams installs the Urine Processor Assembly/Distillation Assembly in the Water Recovery System rack on the ISS (Credit: NASA)

Life Support Systems must be conceived as an integrated sum of unit operations. This requires on one hand, a systemic approach of complex, highly branched systems with important feedback loops and, on the other hand, the study of a set of unit operations in charge of the elementary functions constitutive of the entire Life Support System. The technologies must be developed in a generic way, considering that the final technical solutions will depend on the constraints and on the objectives of the mission's scenarios. The modelling approach by knowledge models constitutes a mandatory guideline for evaluating and designing the processes. This also leads to base control and management strategies. This is the brain-level of the man-made ecosystem; it is materialised by the mathematical deterministic modelling supporting the understanding of the system and subsystems at various interacting scales; this also allows for simulation of the different interacting parts of the system. This brain-level description also contains the fundamental laws of physics and chemistry, starting from conservation laws (conservation of elements – carbon; hydrogen; oxygen; nitrogen; phosphate; sulphur - that is of primarily importance for closed systems – energy conservation laws…etc.) with special attention for cycles and fate of micro-contaminants in the system.

The current ESA strategy puts priority firstly on air and water supply, and secondly on waste and food management. First independent units should be developed, which gradually can be coupled to fully closed systems (Klein, 2009). Current life support systems are indeed functional and very efficient using multiple independent processes units. Although open-loop systems have been used successfully in the past for short-duration missions, the economics of current and future long-duration missions in space will make nearly complete recycling of air and water imperative. A variety of operations will be necessary to achieve the goal of nearly complete recycling. These include separation and reduction of carbon dioxide, removal of trace gas-phase contaminants, recovery and purification of humidity condensate, purification and polishing of wastewater streams, and others. However, it should be demonstrated that these modular systems could be integrated into fully closed loop systems that are equally efficient or even better than the systems currently applied in space.

Also model-based development of technologies is mandatory to utilise and exploit extra-terrestrial planet resources for human life-support system replenishment (ISRU). The development of those processes must be conceived in a generic way in order to be adaptable to a broad variety of applications and environmental conditions (non- terrestrial gravity, low external pressure, radiation exposure, etc.)

While other space agencies (e.g. American, Russian) have reduced or other agencies only recently begin (e.g. China, Japan) their activities in this area, Europe has continued to invest in this topic over the past 3 decades. A large know-how has been gathered and expertise been build, making Europe a leader on this topic, with a large potential to further grow. Following the opinion of Gitelson and Mc. Elroy in 1999 "… elements of a complete recycling system (MELiSSA) were developed fundamentally, which is traditional in European culture, putting together separate links elaborated in several European countries which is a good example of international co-operation".

Proposed investigations and recommendations

- Improve understanding and functioning of closed loops via multiple parameter analysis and modelling with dedicated multi-physics and multidisciplinary algorithms and software tools, including models for thermo-fluid-dynamics, biological processes, human metabolism and respiration, urine and faecal production, etc.
- Develop adequate mathematical models and algorithms to allow correct simulation and prediction of system performance in a multiple implemented conditions or constraints. This can be a valuable alternative for empirical, costly tests non-fully representative of all conditions. If one can predict the outcome, it may allow reducing considerably the risk, preparing spare parts, addressing non-nominal modes, etc.
- Identify needed robust control strategy and buffer capacity, and start-up and emergency storage scenarios.
- Develop supporting databases containing actual data on tested equipment, biological processes, plants, human, etc.
- Develop models describing the fate of micro-contaminants on the molecular level and develop countermeasures for adverse effects.
- Provide conclusive demonstration for the closure, including integrated testing.

Terrestrial interest and application

Modelling and understanding issues are the basis of current improvements of different processes. Any thorough understanding of chemical and/or biochemical processes has potential applications in industrial engineering, whatever the domain, from environmental processes to pharmaceutical processes.

Closed loop recycling and production systems are useful platforms for eco-toxicological research. Miniaturised artificial ecosystems are of interest for investigating in more detail the ecological impact and fate of micro-pollutants in ecosystems (e.g. fate and accumulation of xenobiotics, biocides, antibiotics, hormone derivatives, and pharmaceutical compounds). Improved effluent polishing systems could for example also be useful for removal of bioactive pharmaceuticals in hospitals, municipal wastewater streams, etc.

For terrestrial applications, closed loop waste water recycling systems could be of interest for applications on boats and cruise ships, in remote hotels (eco-tourism), remote stations for exploration and/or exploitation of remote area's (e.g. Antarctica, dessert…etc.).

3.2.3. Key Issue 3: Further develop Life Support subsystems and components for long-duration space flight and planetary surface mission phases

Background and European strengths

Any LSS is composed of an assembly of different systems and subsystems supporting different functions and unit operations (e.g. separation, evaporation, reaction, and bioconversion). Depending on the mission's scenario and on the targeted degree of closure of the LSS, physical systems could be involved alone whether in association with chemical reactors some chemical transformations and other functions can be envisaged. Association with biological compartments allows food production to be at least partly supported. If no chemical transformation is included, physical systems are sufficient (adsorption of CO_2, water purification…. etc.). In that case all consumables are refurnished (O_2, food, part of water). If O_2 is regenerated (by Sabatier process by example) chemical transformations are mandatory. If carbon and nitrogen recycling is envisaged, LSS must include food production calling for biological processes. Whatever the inherent large diversity of the possible life support subsystems and their hybridising in the global system (that calls once more for a generic engineering approach in terms of metrics and of modelling) there are different degrees of maturity for use of such subsystems for human space missions.

Figure 6: Cosmonaut Mikhail Tyurin performs an inspection of the Plants-2 experiment on the ISS (Credit: NASA)

Adsorption processes, for instance, have historically played a key role in life support on U.S. and Russian piloted spacecraft. These processes are good candidates to perform separations and purifications in space due to their gravity independence, high reliability, relative high energy efficiency, design flexibility, technological maturity, and regenerative nature (DallBauman and Finn, 1999).

Another example comes from the use of bioreactors and higher plants chambers (HPC). Presently, bioreactors and HPC for terrestrial applications have relatively low specific volumetric bioconversion rates. Consequently their energetic efficiency may be questionable and they require among others installations with large masses and volumes, energy supply and maintenance time. For space missions, and especially for long-term missions, knowing that masses and volumes and resources will be highly constrained (Salisbury, 1999), bioreactors and HPC must have to be strongly intensified and miniaturised. In addition operational and biological processes will need to be adapted to the space environmental conditions (Haque et al. 1993; Monje et al., 2003).

New technologies and materials are developed every day and there is still room for improvements that should be investigated for future long-durations space missions. In addition, a detailed characterisation and understanding of novel proposed processes under space flight conditions (reduced gravity, radiation exposure, etc.) is a prerequisite (Haque et al. 1993; Monje et al., 2003).

A large community of scientists is involved in environmental biotechnology and active in food and pharmaceutical industry in Europe.

Proposed investigations and recommendations

- Develop and test prototypes for regenerative LSS in relevant environmental conditions (e.g. ground, modified-g, radiation, pressure, temperature, light, ISS, lunar lander) including more efficient microbial bioreactors and plant growth chambers and dealing with:
  - Air regeneration
  - Water regeneration (e.g. filtration)
  - Waste management (e.g. incineration)
  - Genetic stability of biological systems
- Improve efficiency and yield of biological conversion
- Characterise performances of the biological elements in relevant environmental conditions (e.g. modified-g, radiation, pressure, temperature, light)
- Investigate genetic stability of the essential biological specimens in reactor systems and space environment
- Capture and take into account gaps that currently emerge (and many more will in the future) from LSS operations both in space and on Earth (e.g. ISS, submarines), even in very classical systems, to make a lessons learned catalogue available to a wider community
- Improve understanding of multi-phase mass / heat transfer processes under modified-gravity and incorporate solutions into equipment design

Terrestrial interest and application

This issue is relevant to domestic waste treatment and water recycling, zero-emission technology, submarines, isolated extreme environments.

Synergies with biotechnological research and developments in agriculture, food production and processing, pharmacy, waste treatment for high valuable product recovery can also be highlighted.

3.2.4. Key Issue 4: Improve autonomy of LSS via monitoring and control

Background and European strengths

As in any system that is in continuous operation, crew operational mishaps or technical failures (e.g. mechanical or electrical failures of pump, detector, valve, etc.) can occur and have to be taken into account. Continuous process monitoring and control is needed.

Presently, the quality of, for example, the water stored or produced in the life support system of the spacecraft such as ISS, is off-line and often relying on ground analysis equipment. This introduces large response times, and makes any life support system dependent on ground equipment. For future space exploration missions, more advanced, autonomous in-situin-situ on-line process monitoring and control equipment is required. This is especially true if man-made ecosystems are used as regenerative life support systems, as they differ from their prototype biosphere by the principle of control (Farges et al. 2008). The Earth Biosphere is sustainable by stochastic control and very large time constants. By contrast, in a closed ecosystem, a deterministic control may often be a prerequisite of sustainable existence. In addition, future regenerative life support systems will be an assembly of subsystem in a complex architecture, and their optimisation will only possible if the design as well as the control is based on a strong and advanced control strategy.

This, in terms, calls for a as complete as possible fine understanding of the different levels of the system, handled by mathematical modelling. Mathematical modelling accounts for the deterministic aspect of the control. This is particularly true for a complex assembly of several subsystems, interacting with completely different time constants and mass and energy flows. Therefore process monitoring and control requires a multilayer (hierarchical) approach. The reliability is included in a thorough understanding of the processes (including living organism's behaviour) and using the basic principles of mass, energy, exergy (entropy), momentum conservation laws.

Proposed investigations and recommendations

- Take advantage of existing state-of-art systems currently applied in other research such as environmental sciences (e.g. real time water quality) and biotechnology (e.g. bioprocesses control in pharmacy) and adopt for spaceflight
- Thorough characterisation and understanding of the different subsystems and processes what-

ever the level: genetic and metabolic behaviour for microorganisms and higher plants, analysis of coupling between physical phenomena (transfer kinetics and physiological behaviour for living organisms), mass and energy conservation for integrated processes, kinetics responses and time evolution for subsystems, etc.

- Support developments of miniaturised sensors, network management, control modelling, algorithms and software for use in the spaceflight environment
- Perform extensive integrated system testing including software, as many unresolved issues might arise from the system interactions, not the individual subsystems alone. Sub-systems may often satisfy their individual requirement, yet the integrated system fails due to overlooked interface requirements or interactions (Graf et al., 2002).

Terrestrial interest and application

Management of complex systems is known to be a major challenge of 21st century (Edgar Morin). Process engineering (based on chemical engineering principles) and systems engineering (based on a hierarchical approach of control of interacting subsystems) are the clues for modern developments of industrial processes, whatever the size and the functionality. When developing and installing a rationale for a specific purpose such as life support systems for space applications (especially systems including living organisms), the methodology and the approach will be completely transferable to other applications. Controllability, modularity and reliability requirements for LSS are excellent examples of future developments in modern industrial technology. Applications to any environmental process are straight forwards.

3.2.5. Key Issue 5: Improve LSS robustness, reliability, availability, maintainability, safety, acceptability in long-term integrated operations

Background and European strengths

Any failure in a life support system can have severe consequences for human life (suffocation due to lack of O2 or excess CO2 water and food shortage, disease, etc.), but potentially also for infrastructure (fire, explosion) and economically (e.g. abort mission). Thus, life support systems are by definition required to be highly safe, reliable, available, and low maintenance. For future manned mission beyond LEO, where fast rescue to Earth will be no longer possible, this requirement will only become more stringent. For long-durations missions, life support systems will have to be error-free over a longer time frame.

Bioreactors and biotechnological processes are used worldwide in our daily life on Earth. The actual scientific and technological know-how is very high. For example, large volumes of industrial and domestic waste water is treated in biological basins, single-use bioreactors up to 2,000 m3 are successfully used every day in the pharmaceutical or food industry for production of e.g. medicines, fermented beverages. However, currently, still no bioreactor has been accepted for application in space, but showed promising results during the 90-day study at NASA JSC (LMLSTP Phase III, 1997). Unlike natural ecosystem on Earth, miniaturised artificial closed loop ecosystems used as BLSS in space, lack buffer capacity and therefore are believed to be much more challenging to control. But conceptual studies have shown that closed loop controlled ecological life support system is not only feasible, but also eminently practical (Schwartzkopf SH., 1997). Nevertheless, the perception and 'general acceptance' of the recycled product, produced directly from waste in only a limited number of steps, remains still and issue, which should perhaps be addressed at a "collective" social, psychological and education level.

It is essential to test hardware for longer-duration functionality and in the correct representative environment for the planned mission (e.g. Moon or Mars conditions), and using representative air, water, food and waste streams for recycling processes. Testing individual subsystems to interface performance requirements in clean rooms on Earth or in ISS environment are typically insufficient to address the complex system interactions, and integrated system tests in realistic operational environments are difficult (Allen et al., 2003), often not planned nor budgeted, resulting in on-orbit surprises.

Russia has built the longest and strongest expertise over the last 50 years in long duration testing in integrated and confined habitats (e.g. BIOS facilities in Krasnoyarsk, IMBP facility in Moscow). Large scale integrated test facilities were also built in Japan (e.g. CEEF) (Nitta, 2005) and US (e.g. Biosphere 2) (Allen et al. 2003), with variable success. Europe, however, has mainly relied on the Russian expertise through collaborative projects (e.g. MARS100, MARS500), and only recently initiated construction of own facilities and independent investigations (e.g. utilisation of Concordia station on Antarctica - Van Houdt et al., 2009), MELiSSA pilot plant in Spain (Godia et al., 2004), FIPES (Hammersley, 2006) and CAPSULES habitat feasibility studies, etc. Thus, Europe still a large potential to grow in this area develop more expertise and facilities.

Figure 7: A view inside the MELiSSA pilot plant at the University Autònoma of Barcelona (Credit: ESA/UAB)

Large community of scientists and industry involved in environmental biotechnology, bioreactor and greenhouse technology, agriculture and biological waste treatment present in Europe.

Proposed investigations and recommendations

- Development of a thorough understanding of the processes using a systemic (holistic) viewpoint with a particular attention to how the knowledge of the system depends upon the position and scale of experimental observation.
- Improvement of predictability of the system by understanding and modelling in order to found the control strategy and to enlarge the field of conditions of application, including back-up scenario.
- Implement failure tolerant functions
- Design and construct facilities on Earth for long-duration and integrated testing, including several modules of LSS (e.g. reactors, bioreactors, higher plants chambers, separators, purification processes), in combination with other habitat and crew activities (e.g. EVA activities, medical-psychological-behavioural-acceptability aspects). Long duration integrated test facilities must be modular, flexible to accommodate alternative elements, robust and easy to reactivate and expand.
- Application of current HACCP and GMP methods to these processes in order to guarantee the same level of safety (and encourage acceptability) that is now existing for food and pharmaceuticals
- Exploit ISS and other space flight opportunities (e.g. Bion) as a test bed for life support system technology including physicochemical treatment for air regeneration, higher plants chambers, analysis of the effects of microgravity on living microorganisms.
- Test miniaturised components and life support systems on Lunar Lander to assess environmental factors on system performance.

Terrestrial interest and application

In terms of applications, simple and reliable systems are required for numerous applications, including domestic applications (e.g. water treatment) and confined systems (e.g. atmosphere decontamination and treatment for industrial application e.g. nuclear plants, pharmacy, industry of electronics). In terms of waste treatment (agricultural waste, industrial waste, domestic waste) including the treatment the valorisation and eventually the confinement, there are also many potential applications. The development of robustness of such systems is mandatory for many purposes, knowing that future environmental technologies will be much more distributed than today. This calls for an improved autonomy and smaller units. The gains in performance and reliability will be in logical extension of the generic approach that is developed for LSS.

Confined manned habitats on Earth or in Space could also be prototypes allowing profound testing and evaluation of sustainable, i.e. environmentally-conscious (green), housing and working designs and technologies. Such habitats are unique test platforms for recycling processes, and for sociological and eco-toxicological research.

The perception and general acceptance of recycled products (e.g. food products), produced directly from waste in only a limited number of steps, remain still an issue, which should perhaps be addressed at a collective social, psychological and education level. Similar approaches could be valid for a larger number of topics, including GMO's.

3.2.6. Key Issue 6: Screen and develop high performance materials for LSS

Background and European strengths

The design, materials, and systems that are commonly used for bioreactors for terrestrial processes, are not all suitable and applicable in space. New 'space compatible' materials and systems need to be developed. This can involve improvements of artificial light systems, anticorrosion materials and shielding materials. In Europe several companies are running with antimicrobial coatings (mainly Silver). New approaches to use bio-inspired coatings are running (for example: BIOCOAT at University of Liège (B). In the frame of a government funded project OHB (D) is also testing bio-inspired coatings based on proteins for Space Habitat application) – Life Science people are more and more involved.

Proposed investigations and recommendations

- Develop materials and solutions to reduce mass and volume of life support systems
- Develop and test materials to be compatible with changed fluid and gas behaviour in space environment
- Improve biocompatibility of materials for safe contact with crew or for use in biological life support systems, and for long-term use in sealed environments
- Incorporate new functionalities (e.g. flexible, transparent, surface tension control, 'bio-functional', biodegradable, resistant to sterilisation, resistant to biofouling, etc.) in materials, also considering "bio-inspired" materials, used for life support systems, working in commonality with industry.

Terrestrial interest and application

Synergies can be identified with materials science and engineering and biotechnology, with potential applications for the medical field, agriculture, food production and processing, pharmacy, waste treatment for high valuable product recovery.

3.2.7. Key Issue 7: Develop and demonstrate capabilities to exploit resources available on other planets (In-Situ Resource Utilisation - ISRU) for life support

Background and European strengths

In-Situ Resource Utilisation (ISRU) implies not only recovery of water but should be investigated much broader. It could for example also include investigations in the potential of rocks (regolith) as sources of oxygen (e.g. 40% of the moon rock is containing bound-oxygen as e.g. silicates.) (Lunar Source Book, 1991; Churchill, 1997; Spudis, 1996; Heiken, 1995; Silberberg, 1985; Nealy, 1988; Hayashida, 1991; Anderson, 1994; Artemis, 1995; Lindsey, 2003) or as shielding material (Townsend, 2005).

Proposed investigations and recommendations

- Evaluate how ISRU affects LSS at the system level
- Establish links with other disciplines for ISRU technology exchange, such as propulsion, radiation protection.
- Develop links with groups traditionally not represented in aerospace necessary for these ISRU tasks (mining, civil engineering, large mass moving equipment)
- Develop technologies to identify and extract relevant resources, e.g.:
    - Test efficacy of Lunar/Mars regolith simulants now, and return samples later, as substrates for growth of candidate crop species. Because of the likely fine particulate size (and small pore space), simulants will need to be retested for plant-growth efficacy in microgravity (ISS), and then real regolith tested at 0.17xg on the Lunar surface and then at 0.38xg on the Mars surface.
    - CO2 extracted from the Mars atmosphere should be tested for ability to support crop photosynthesis.
- Perform demo testing in analogues for ISRU systems operations (large scale)
- Perform demo testing on the moon for specific ISRU technologies for LSS (small scale)
- Improve knowledge of Martian soil from robotic missions, from an ISRU for LSS standpoint (for water and oxygen production)
- Prepare a scenario for ISRU demonstration on Mars

Terrestrial interest and application

Potential synergies with research to improve CO2 sequestration on Earth can be put forward.

3.2.8. Key Issue 8: Improve LSS architecture to increase habitability

Background and European strengths

LSS architecture requirements are:
- maximising usability with high efficiency (simple and practical) and high safety levels (austere) (Jones and Harry, 2003; Jones and Harry, 2010)
- minimising space and mass
- minimising maintenance
- minimising production costs

In principal for safety reasons all systems such as LSS, should be modular – so to speak plug-and-play parts in case a part fails to work in one place the astronaut can put it into another place (Imhof, 2005).

Habitability issues

The LSS and their relationship with aspects of habitability become very prominent during long-term stays (from 6-months onwards). Therefore it is crucial to incorporate specific aspects of habitability as listed below, even if this implies an LSS efficiency decrease.

- Maintenance: Astronaut system time is approximately 30% and mostly incorporates maintaining the systems. This is an important aspect of habitability because maintenance limits free time which is very low already, and thus reduces the quality of habitability. Additionally, issues of malfunctioning can further degrade habitability.
- Noise: The noise level of the LSS is still much too high in the ISS. Every astronaut wears ear plugs because of the approx. up to 60dB of ventilation/fan noise. Reduction of noise levels means a significant increase of habitability. In the quite newly private cabins of Node 2 (2009) the noise levels of the high-speed fans are reduced through thick noise bumper material constructions. However, the noise still has different levels in different modules. For example, the European module is less noisy than the American laboratory module.
- Ventilation: Sometimes crew members suffer from headaches if areas are not sufficiently ventilated (Adams and Constance, 1998). Julie Payette reported headache on her first mission to ISS 1999 , and Chris Cassady had to interrupt a spacewalk

because of a malfunctioning air scrubber and rising CO2 levels . Too much ventilation can cause drafts, which is also perceived uncomfortable by some crew members. Other factors in this area are the composition of air in relation to the pressure. On ISS the pressure levels are different from Earth. they are lower than 1 bar. Thus the mixture of oxygen and nitrogen also is adapted accordingly to fit approximatively the relationship of these factors on Earth.

- Odor: Malfunctioning toilets cause a serious degradation of habitability not only through reduced comfort, but also through odor issues. In 2009, astronauts Frank de Winne and Mike Barratt (USA Today, 2009) had to do major repair work on the ISS's toilets. But also in simulation-habitats like the Mars Societies' MDRS in Utah problems with the toilet have occurred .
- Plants: These can also provide non-nutritive benefits and resemble effective countermeasures against deprivation (Imhof, 2003) in isolated/ extreme environments (Bates, 2009). In Mars500 people were encouraged to work in the greenhouse if they wanted, which increased crew cohesiveness and relaxation (Imhof and Schartner, 2001).

Apart from large European industries such as TAS-I or EADS Astrium, there are also SMEs with a very high capability of advanced space architecture and design expertise including a history in working with the big industry and the space organisations NASA and ESA. (e.g. LIQUIFER Systems Group, Architecture and Vision)

Proposed investigations and recommendations

There has been some research in the area of the relationship between LSS and habitability (ESA, 2004; Broyan, 2010; Imhof, 2005), but for long-duration exploration missions this relationship needs to be studied in much more detail.

- Identify technical habitability factors of LSS: Which requirements/factors of the Life Support Systems are vital for habitability, easy maintenance, comfortable and productive environment.
- Identify trade-offs between individual human-related comfortable environments and the LSS (lessons learned from ISS, previous space stations, and analogue simulations).
- Identify trade-offs between habitability and LSS requirements: Where does habitability become detrimental for LSS requirements and vice versa? Consequently, establish optimal conditions where both taken together lead to maximized productivity.
- Ergonomics of the LSS-Human-Machine Interface: How must the machinery be built so that there is easy maintenance and easy access to adjust comfort levels of fans, air ventilation, water recycling and food production).
- Safety of the LSS-Human-Machine Interface: How must the systems be designed in order to optimise safety, taking into account efficient operation.

Terrestrial interest and application

Derived from the MELiSSA ECLSS there have been already applications regarding grey water treatment for hotel complexes. The Dutch company IP-STAR is currently implementing these applications. Furthermore, grey water treatment can become important to every major urban development, especially new ones and can lay the path for a more sustainable way of living on Earth. This applies to all Life Support Systems technologies. Especially in deprived urban areas where good water quality is lacking, there could be affordable spin-off applications of Advanced Life Support Systems for a more habitable environment (Adams, 2004; Imhof, 2007).

LSS and habitability are important issues on ISS, just like they are on Earth, in offices or spaces with full artificial air-conditioning. The room temperature and air circulation (including other factors of HVAC - heating, ventilating, air-conditioning) are always issues of discussion amongst the office people/astronauts because they depend on personal perception. Nevertheless, well-working LSS or HVAC which are easy to adjust are simply vital for a comfortable and productive working environment. Parallel studies on Earth and in space might reveal similarities and allow drawing conclusions from earlier Earth research.

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4 Annex: Expert Group Composition

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