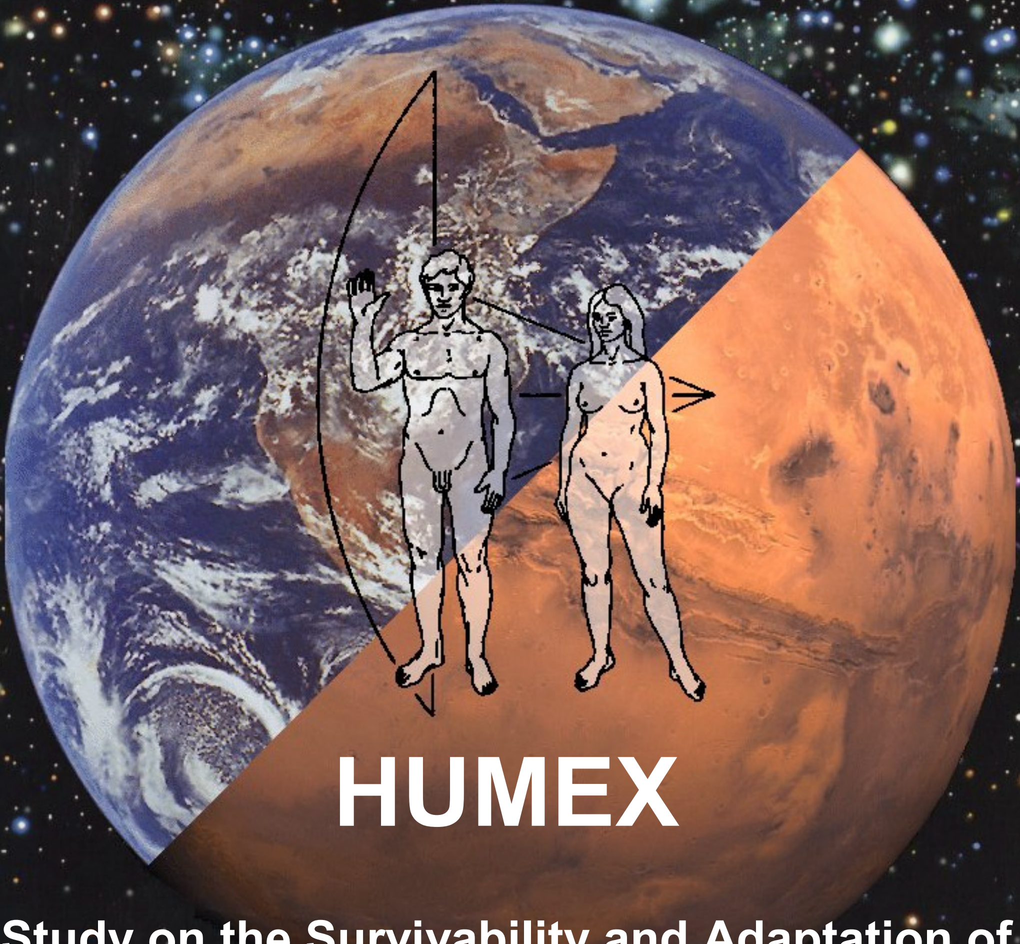

HUMEX

Study on the Survivability and Adaptation of Humans to Long-Duration Interplanetary and Planetary Environments

ESTEC/Contract No. 14056/99/NL/PA

Executive Summary

HUMEX,
a Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions

ESTEC/Contract No. 14056/99/NL/PA

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EXECUTIVE SUMMARY

After the realization of the International Space Station (ISS), human exploratory missions to Moon or Mars, i.e. beyond low Earth orbit (LEO), are widely considered as the next logical step of peaceful cooperation in space on a global scale. Besides the human desire to conquer the outer limits of habitability, human exploratory missions are driven by several aspects of science, technology, culture and economy. If Europe plans to take an active role in future human exploratory missions, it should rely on the experience and achievements gained in conjunction with previous human missions in Earth orbit (e.g., Spacelab, MIR) and with the ongoing activities on the ISS. There are several fields in life sciences, in which Europe has gained a competitive role, such as in human physiology and countermeasures, gravity biology, and radiation health issues as well as in advanced life support technologies, as recently documented by the European Science Foundation in an assessment of ESA's Life and Physical Sciences Program.

Long-duration missions beyond LEO offer a variety of tremendous challenges to various disciplines in sciences and technology. This HUMEX study has concentrated on human health related aspects: it provides a critical assessment of the human responses, limits and needs with regard to the stress environments of interplanetary and planetary missions. Emphasis has been laid on human health, well-being and performance care, such as radiation health issues, adaptation to microgravity and reduced gravity, psychology issues and health maintenance, respectively, and on advanced life support developments. The overall study goals are as follows:

- to define reference scenarios for a European participation in human exploration and to estimate their influence on the Life Sciences and Life Support requirements;
- for selected mission scenarios, to critically assess the limiting factors for human health, wellbeing, and performance and to recommend relevant countermeasures;
- for selected mission scenarios, to critically assess the potential of Advanced Life Support Developments and to propose a European strategy including terrestrial applications;
- to critically assess the feasibility of existing facilities and technologies on ground and in space as test beds in preparation for human exploratory missions and to develop a test plan for ground and ISS campaigns;
- to develop a roadmap for a future European strategy towards human exploratory missions, including preparatory activities and terrestrial applications and benefits.

The study has been led by DLR with cooperation of MEDES (France), DERA (UK), Astrium (Germany) and the University of Clermont (France).

Mission reference scenarios

The reference scenarios have been selected from existing plans, such as the NASA reference mission to Mars and the ESA Space Exploration and Utilization Study. Based on the understanding that

- the mission scenarios should be realistic and feasible based on today's technology,
- Moon and Mars should be the target of at least one mission scenario, and
- the mission scenarios should be representative according to existing international plans,

the following three reference scenarios have been agreed upon:

Mission	Target	Description	Crew size	No. EVA**
Scenario 1	Moon	Lunar outpost at the south pole (constant sunlight and potential water ice deposits could be assumed) with 180 days stay on the Moon	4	60
Scenario 2	Mars	A 1000 day Mars mission with about 400 days stay on Mars and the option of in-situ resource utilization (ISRU)	6*	175
Scenario 3	Mars	A 500 day Mars mission with about 30 days stay on Mars	6*	30

*) 4 crew members landing on Mars, 2 remaining in Mars orbit;
**) each EVA includes 2 astronauts for 8 hours maximum

Life Sciences and Life Support requirements.

The safety objectives for the three mission scenarios were chosen on the base of general human health statistics as follows:

- The individual risk of death by illness during the mission shall be $\leq 2\times10^{-3}$/year.
- The individual risk of death by injury during the mission (excluding spacecraft failure) shall be $\leq 4\times10^{-4}$/ year.
- The individual risk of death (all causes, including spacecraft failure) shall be maintained during the mission as $\leq 3\times10^{-2}$/year.

Using classical reliability requirements for human space missions, reliability assessments have been performed for every phase of the three reference missions, yielding the following overall mission reliability objectives which are compatible with the mission safety objectives:

Mission	Target	Overall mission reliability
Scenario 1	Moon	0.949
Scenario 2	Mars	0.919
Scenario 3	Mars	0.936

The probabilities of occurrence of diseases and injuries during the three mission scenarios which have been assessed from a weighted compilation of epidemiological data derived from analogous hazardous situations and which are not yet influenced by the specific spaceflight parameters, give the following values:

		Probability of occurrence					
Health event	Incidence per person and year	Scenario 1		Scenario 2		Scenario 3	
		Earth-Moon-Earth transfer	Stay on Moon	Earth-Mars-Earth transfer	Stay on Mars	Earth-Mars-Earth transfer	Stay on Mars
All causes and illness	17.8853	1.5674	35.2667	175.452	102.861	126.078	5.8778
Estimated mortality by illness	0.0020	0.0002	0.0039	0.0196	0.0115	0.0141	0.0007
Estimated mortality by injury (excluding spacecraft failure)	0.0004	3.5E-05	0.0008	0.0039	0.0023	0.0039	0.0023
Estimated mortality by illness or injury (excluding spacecraft failure)	0.0024	0.0002	0.0047	0.0236	0.0138	0.0180	0.0030

The human needs and wastes produced have been estimated based on presently available techniques used onboard of existing spacecrafts to amount to:

Scenario	Mission	needs (kg)	wastes (kg)	energy (kJ)
1	Earth-Moon-Earth	327.6	293.6	462 080
	stay on Moon	22 217.9	21 736.6	10 396 800
2	Earth-Mars-Earth	108 306.3	108 137.4	51 724 080
	stay on Mars	64 842.6	63 395.2	30 324 000
3	Earth-Mars-Earth	77 999.9	77 889.6	37 255 200
	stay on Mars	1 390.3	1 080.1	1 732 800

These estimates on life sciences and life support requirements are well in agreement with previous analyses of crew health issues during long-duration space flights.

Limiting factors for human health, wellbeing, and performance and relevant countermeasures

Exploratory missions to Moon and Mars including the establishment of a permanently crewed base on the lunar surface will add a new dimension to human space flight, concerning the distance of travel, the radiation environment, the gravity levels, the duration of the mission, and the level of confinement and isolation the crews will be exposed to. This will raise the significance of several health issues, above all radiation health, gravity related effects as well as psychological issues, becoming a possible limiting factor to human adaptability during these missions. The safety provided so far in LEO has to be replaced by adequate means and measures available and effective within the spacecraft or habitat itself. Crew health and performance have to be secured during transfer flights, during planetary surface exploration, including EVAs, and upon return to Earth, as defined within the constraints of safety objectives and mass reduction. Thus, prior to the design of an exploratory type mission (hardware and operations), numerous key issues of Life Sciences need to be addressed.

In this study, the human-related aspects, such as health, well-being, performance, needs, and necessary countermeasures, with regards to limits, survivability and adaptation in long-duration exposures to interplanetary and planetary environments are critically assessed. For all three scenarios, the impact on human health, performance and well being is identified from the view point of the effects of cosmic radiation including solar particle events, of microgravity (during space travel), reduced gravity (on Moon or Mars) and abrupt gravity changes (during launch and landing), of psychological issues as well as general health care. Countermeasures as well as necessary research using ground-based testbeds and/or the ISS are defined.

Radiation health issues. Since the very beginning of human space flight, ionizing radiation has been recognized as a key factor of the space environment, potentially limiting the duration of human sojourn in space by its deleterious effects on crew health, performance, and – finally - life expectancy. Depending on mission scenarios, this environment consists of varying combinations of primary galactic, solar, and trapped radiation components, each of which being mixtures with vastly differing radiobiological effectiveness and each of which giving rise to equally complex secondary radiation upon passage through matter, including the human body itself. The parameters relevant for radiation exposure assessment in exploratory type missions include (i) mission duration, (ii) solar distance, (iii) solar cycle time, (iv) mass shielding, and (v) mission phase. Late effects, such as enhanced morbidity or mortality from malignant cancers occurring up to 20 and more years after exposure have to be considered as well as early effects which may comprise morbidity such as anorexia, fatigue, nausea, diarrhea, and vomiting (the symptoms of the so called prodromal syndrome) or cataract formation and erythema and early mortality within days to a few weeks from failures of the hematopoetic, the pulmonary and the gastro-intestinal system. Estimates for the total radiation doses conceivably to be incurred at the blood forming organs (BFO) from galactic heavy ions (GCR) and from solar particle event (SPE) irradiation during the three mission scenarios indicate that exposure levels will exceed the limits set forth in radiation protection guidelines for LEO, e.g., ISS operations:

	Reference mission	Total mission equivalent BFO dose (Sv) behind shielding		
		1 g cm^{-2} of pressurized vessel	5 g cm^{-2} of equipment room	10 g cm^{-2} of radiation shelter
GCR during solar minimum	Scenario 1	0.195	0.177	0.161
	Scenario 2	0.993	0.918	0.852
	Scenario 3	0.828	0.754	0.687
GCR during solar maximum	Scenario 1	0.074	0.070	0.066
	Scenario 2	0.420	0.383	0.364
	Scenario 3	0.317	0.299	0.280
SPE (worst case)	interplanetary	3.52	1.93	1.26
	surface Moon	1.76	0.97	0.63
	surface Mars	0.31	0.28	0.25
Annual limit	LEO (ISS)	0.50		
	Radiation workers	0.020		

The uncertainties limiting the accuracy of these estimates of radiation exposure in exploratory missions arise from the physical data, especially from the unpredictable stochastic nature of SPEs, and to larger extend from the radiobiological assessments with uncertainties up to a factor of 5 which may impose a tremendous and potentially prohibitive design penalty on any mission design attempting to counter the perceived risks by providing, e.g., mass shielding designed to prevent radiation injury as estimated under worst case assumptions.

In order to minimize the risk from space radiation - and hence to extend the limits of survivability and adaptation to space radiation during long-duration missions - future research and development required may be grouped into three categories, concerning

- the prior adequate quantitative risk assessment for accurate mission design and planning in order to minimize the expectation value of Healthy Lifetime Lost (HLL),
- the surveillance of radiation exposure during the mission for normal and alarm operational planning and for record keeping, and
- countermeasures to minimize health detriment from radiation actually received by selecting radiation resistant individuals or by increasing resistance, e.g., by radioprotective chemicals. The opposite selection process whereby individuals with identifiable genetic disposition for increased susceptibility to spontaneous - and implied - to radiogenic cancerogenesis are detected, will in any case be part of the standard crew selection, but the exclusion of susceptible applicants itself is not considered a countermeasure.

In addition to the standard countermeasures such as avoidance of exposure by adequate shielding and mission planning or by chemoprotective and even nutritional measures, the most important countermeasures will consist of radiobiological research activities which have the potential to reduce significantly the uncertainty of our risk estimates. These uncertainties are related to the potentially unique radiobiological properties of galactic heavy ions or to the possible modifications of space radiation effects - either synergistically or antagonistically - brought about by the changes in the humoral status of the human body during spaceflight. This status is not only shifted to a new set point by microgravity but may also be altered in response to general stress – including psychological stress. Terrestrial research on heavy ion accelerators will have to focus on the effects of single heavy ions on individual cells as they are investigated, e.g., in the recently developed microbeam techniques whereas a definite answer concerning the modification of radiation effects by the exposure conditions in space will only be found in properly designed - most likely animal - experimental studies on the ISS or on a lunar base. Finally, the criteria presently used in deriving space radiation exposure limits need to be redefined in order to allow for an integrated, unified risk management and design approach which - among other advantages - explicitly considers the repercussions of radiation protection measures like shielding design or mission planning on the overall mission success probability. The (probabilistic) expectation value of the Healthy Lifespan Lost (HLL), i.e., the number of healthily lived years lost due to an exploratory space mission would serve such purposes more neatly than the presently invoked criteria and its minimization would allow for a combined balanced treatment of early and late radiation effects on an equal footing.

Microgravity, reduced gravity, and general health issues. The transition through various levels of gravity, such as from 1×*g* through hypergravity to microgravity during launch, long-term exposure to microgravity during interplanetary transfer, transition from microgravity to hyper-gravity during de-orbit and stay at reduced gravity on the celestial body – to mention just the one-way trip to the moon or to Mars - have major implications for the astronaut health control. This concerns the deconditioning symptoms, such as loss of muscle and bone mass, a reduced cardiovascular and physical capacity and changes of motor skills. Additional to this gravity-related risk for astronauts on planetary missions is the risk of unavoidable concurrent general disease occurrence which has to be faced in any long-term absence from home facilities. This latter risk is especially severe for missions to Mars, where fast emergency return to Earth is impossible. Crew health and performance have to be secured during transfer flights, during planetary surface exploration, including EVAs, and upon return to Earth, as defined within the constraints of safety objectives and mass reduction.

Unrestricted adaptation to microgravity leads to physical deconditioning such as loss of muscle and bone mass, a reduced cardiovascular and physical capacity, and changes in motor skills. From both an ethical and medical point of view, it is unacceptable to expose astronauts to microgravity on long duration flights without attempting to prevent or reduce these induced disorders. Deconditioning greatly increases the risk to astronaut's health not just after return to 1×*g* conditions, but also during strenuous work in the space vehicle, during EVAs, and on a planetary surface. These deconditioning changes, to a certain extent analogous to the physiological deconditioning observed in elderly people, can be life threatening, especially in emergency situations, or when considering that EVAs on a planetary surface will involve physically intense work.

Current evidence indicates that the countermeasures presently used (LBNP sessions + fluid /salt load before return to gravity + wearing of anti-g suit during return and first few days in gravity) have improved the control of the orthostatic intolerance. The use of a short arm centrifuge can only be considered as a potential countermeasure for planetary exploration under the following conditions: (i) if the neurosensory induced discomfort has proved to be acceptable after a certain training effect; (ii) if beneficial effects on bone loss have been demonstrated; and (iii) of benefits on exercise capacity have been shown.

In order to maintain crew health and operational efficiency during exploratory missions, a research program is recommended including research

- in gravity-related health issues, such as on musculoskeletal disorders, neurosensory disorders, and orthostatic intolerance;
- in general health issues, with emphasis on those phenomena which are considered to be specific for the mission scenarios studied, e.g. long-term stay in a close confinement, or which might be indirectly influenced by the space flight conditions, such as infectious diseases, neoplasm risk, endocrine, nutritional and metabolic disorders, general cardiovascular diseases, digestive disorders, and injuries;
- in development of appropriate countermeasures in view of long-term exploratory missions.

Whereas a certain fraction of this research can already be performed using short-duration space missions, e.g., taxi or Shuttle flight to the ISS, satellites, or terrestrial simulation facilities, the major and more important part of these studies requires long-term exposure to space flight environment or comparable simulated conditions. These measures have also the potential to enrich various fields in clinical practice and health prevention on Earth.

Psychological issues. Living and working in a space habitat involves chronic exposure to many different stressors which are

- unique for the space environment (e.g. microgravity, alterations of usual dark-light cycle);
- related to the technical constraints of a space habitat and its life support system (e.g. confinement, deprivation of range of usual surroundings, limited facilities and supplies for personal hygiene, elevated noise level, elevated CO_2 concentration in the ambient air);
- related to the mission specific operational and experimental workload of astronauts (e.g. work underload and overload, sustained stress); and
- arising from the psychosocial situation in a space habitat (e.g. isolation of family and friends, lack of privacy, restricted and enforced interpersonal contacts).

They can entail detrimental effects on the behavior and performance of astronauts. Exposure to these different stressors can be assumed to induce different behavioral stress responses of the individual astronaut or the entire space crew which can emerge in three interdependent effects:

- impairments of cognitive performance and perceptual-motor skills,

- maladaptive individual behavioral reactions, and
- disturbances of interpersonal relationships within the space crew and between space crew and ground personnel.

Generally, future long-duration exploratory space missions to Moon and Mars can be expected to involve the same range of psychological issues and risks which have been reported from long-duration orbital flights, simulation studies and expeditions into analogue environments. Beyond that, they will present new challenges which can seriously raise the risk associated with these issues as compared to what has been reported, so far, from other relevant settings. Psychological relevant factors are

- mission duration;
- crew size and composition;
- degree of isolation and social monotony;
- crew autonomy;
- evacuation in case of emergency;
- availability of support measures, such as ground-based monitoring, audio/video transmission, e-mail up-/downlink, internet access, onboard entertainment, , and visiting crews;
- visual link to Earth.

Missions to Mars will not be comparable to any other undertaking humans have ever attempted. Even though some aspects of these missions are shared by other settings (long-duration stays on orbital space stations, historical expeditions to unknown parts of the Earth, overwintering in Antarctica, long-term submergence in submarines), altogether the physical and psychological demands given by the long distance of travel, the duration of permanent living under dependence of automated life-support systems, the degree of isolation and confinement, and the lack of short-term rescue possibilities in case of emergencies will exceed those of anything else humans have ever been exposed to. The currently available data base clearly is too small to derive definite risk assessments and further research will be needed. In addition, a much more detailed understanding of the concrete scientific and operational demands of space crews and the design of their habitats on exploratory missions is needed before the psychological issues associated with these missions can finally be assessed and appropriate countermeasures can finally be developed.

The concept and elements of psychological countermeasures recommended for exploratory missions consist of two different levels:

- basic issues of environmental engineering, including the habitat design, the design of autonomous (life support) systems, and scheduling of work design and work rest; and
- specific psychological measures to facilitate adaptation of the astronauts to the living conditions in space, including basic screening and selection, psychologically guided crew composition, psychological training, in-flight monitoring and support of crew behavior and performance, and post-flight support.

Several methodological approaches can be considered in order to conduct the recommended fundamental research and countermeasures development, including but not limited to research during long-duration orbital spaceflight (ISS), research in appropriate analogue natural environments like Antarctica or undersea habitats in cooperation with national organizations responsible for these fields, secondary analyses of existing data-bases from analogue natural environments like Antarctica and undersea habitats, and research during ground-based simulation studies in isolation chambers (including altitude and hyperbaric chambers equipped with life-support systems). These psychological data are also required for developing and applying an Integrated Performance Modelling Environment (IPME).

Advanced life support systems

The requirements posed on an environmental control and life support system (ECLSS) change drastically, whenever humans are subjected to exploratory types of missions facing interplanetary and planetary environments. Whereas, so far, the ECLS techniques available are based almost entirely on physico-chemical processes, exploratory missions demand for alternative methods of ELSS, including

- biological/bioregenerative processes mimicking natural processes of our biosphere on Earth, and
- the utilization of natural resources available on extraterrestrial bodies for as much purposes as possible.

Different ECLS relevant issues have to be considered for the transfer phases from Earth to the Moon or to Mars, respectively, and back, and for the stay on the surface of the celestial body. On a Martian mission, e.g., the main difference between transit and Mars stay phase is due to the fact that only limited space and power is available on the transfer vehicle, whereas, on the surface of Mars, additional space will be available as well as sufficient amount of energy due installation of additional habitat(s) (e.g. inflatable structures, local resources) and (eventually nuclear) power plant(s) which may be brought to Mars prior to the arrival of the crew.

Physico-chemical life support systems. Concerning advanced life support systems for space applications, a mature knowledge is available in Europe with regard to air/atmosphere conditioning and water and waste treatment:

Function	Technology	Status
Air circulation	centrifugal fan	APM, flight scheduled in 2004
Temperature and humidity control	- plate/fin heat exchanger - rotary water separator	APM, flight scheduled in 2004
	- membrane condensing h/x	technology demonstrator
CO_2-control	Non-regenerative: LIOH	terrestrial application, EVA technology
	Regenerative: solid amine	advanced breadboard
CO_2-reduction	Sabatier reactor	technology breadboard, no µg water recovery inc.
O_2-Generation	Fixed Alkaline Electrolyte (FAE)	advanced breadboard, flight experiment planned
Methane cracking	high temp. pyrolysis	initial breadboard tests
Contaminants control	catalytic oxidisers	initial breadboarding
	regenerative charcoal- type absorbers	feasibility checks
O_2-reclamation	integrated / modularised system of solid amine, Sabatier and FAE	closed chamber tests, 3/7 person load
Toilet	compaction, liquid separator	stopped with HERMES
Water management	conditioning, storing, distribution	stopped with HERMES
	liquid/ gas separators	breadboarding with membr.
Waste management	collection, compacting, conditioning, storing, processing	stopped with HERMES

In view of this broad experience in ECLSS for human space flight, it is recommended, that cabin air management should be the prime focus in the further development of ECLS technologies in Europe, such as the air revitalization system demonstrator consisting of a regenerative CO_2 scrubber attached to a Sabatier reactor is suggested as a promising process of regaining O_2 back to the cabin air. Due to the necessity to close the material loops, handling of water in its liquid or vapour state is a task inherent to the various air-related process techniques, too. Concerning exploratory missions, the physico-chemical life support technologies will remain the backbone of any ECLSS, however bioregenerative techniques will be integrated complementary to physico-chemical LSS, especially for food and waste management.

Biological life support systems. The components for the biological regeneration of a human habitat so far considered, include

- algae, mainly for the conversion of CO_2 to O_2;
- higher plants, for varied source of food, conversion of CO_2 to O_2, and for psychological aspects;
- microorganisms, which are involved in simple controllable processes, such as waste degradation.

There is a wide range of biological components that can be used in such ECLSS with a lot of interrelations between each component and subsystem (biological and/or physico-chemical). A biological life support system (BLSS) must be studied as a whole and not as the result of the studies of individual elements. This is true for the calculation of the closure of the system (what gives the reduction of the mass of the consumables) and for the calculation of the overall mass, volume and are of the system (instrumentation, reactors, closed chamber, power supply systems, cooling systems…).

Beside the closure of the artificial ecosystem, the control of the BLSS must also be considered as an important parameter to integrate in the choices for the design of system. Furthermore, the reliability of the system in case of the failure of one of its element (biomass death or plants diseases) must be considered. For the cases of failure, systems with short life cycle, which can then be restarted quickly would be the preferred choice. For safety and reliability, in any case a biological life support system cannot be based on one unique biological component.

From the present knowledge on the existing BLSS and on the biological component that can be included in BLSS of exploratory missions, the following recommendation can be made:

- Higher plants would be the core in a BLSS for food production.
- Algae are very promising components for atmosphere regeneration.
- Micro-organisms would be a central element of a BLSS. They are the first step in the treatment of the waste produced by the crew or by the other biological component of the system. High closure of the LSS can only be achieved by use of microbial systems. The selection of processes that can be used in term of species involved, efficiencies, reliability and safety is an important challenge. Another important point is that these processes are of direct interest for terrestrial application in waste treatment systems (water, isolated bases, self sufficient building…).

Environmental Monitoring. Environmental components of concern that need monitoring include:

Environmental parameter		Type of monitoring
physical	temperature	continuous
	pressure	continuous
	particulate size and concentration	periodical
chemical	major and trace gas species, e.g. O_2, N_2, H_2O, CO_2, CO, NO_x	continuous
	marker chemicals for overheating of electronics	periodical
	marker chemicals for pyrolysis	periodical
	specific hazardous chemicals from payload experiments, EVAs, fluid systems, waste storage	periodical
biological	microbial species and counts	periodical

In addition to physico-chemical monitoring techniques, bioassays and biosensors should be used in the future for environmental monitoring of air, water, newly produced food etc. in spacecraft and extra-terrestrial habitats. Biosensors are particularly valuable for environmental monitoring when they either provide continuous or near-continuous information about rapid and unpredictable fluctuations in the concentration of one or more parameters simultaneously, or single measurements of the concentration of analytes which are difficult to measure using conventional methods. Biosensors may also offer competitive advantage over conventional methods of analysis if they are more rapid and/or easier to use. In all cases, biosensors should be amenable to miniaturization and integration into multisensor arrays to facilitate analysis via, for example, neuronal networks and chemometrics. Biosensors are absolutely needed to measure biological effects (e.g. genotoxicity, immunotoxicity, biotoxins and endocrine effects) and the concentration of specific analytes which are difficult to detect and are important contaminants of water, waste, or air. The high selectivity properties, good detection limits, and the possibility of at-site measurement at different locations in a spacecraft make them particularly attractive for use in such environmental monitoring situations.

Utilization of natural resources. One of the most attractive options for in situ resource utilization (ISRU) during exploratory missions appears to be the production of propellants and life support consumables from materials of the Moon or of Mars. A significant reduction of the propellant and consumable masses that have to be lifted from the surface of the Earth would dramatically lower mission costs. For hydrogen/oxygen burning engines - the most advanced chemical propulsion systems today - oxygen makes up roughly 80% of this propellant mass. Environmental Control & Life Support Systems (ECLSS/ALS) could also benefit from in-situ resources, depending on the degree of closure of the systems. Products derived from in-situ resources might be used to supplement these systems, e.g., replacing losses due to consumption, leaks or extra-vehicular activities (EVA's). Typical products involved (for breathing, drinking, cooling purposes, buffer gases, potential plant growth in greenhouses, radiation shielding etc.) are O_2, H_2O, N_2, He, Ar, CO_2 and even the fine grained surface regolith.

Among the concepts proposed for the production of lunar oxygen, the most promising ones are:

- carbothermal reduction with methane,
- ilmenite/glass reduction with hydrogen,
- oxidation with fluorine, and
- pyrolysis/vapor phase reduction.

Lunar oxygen production may be different for the "pioneering" period and a later period of "permanent human presence". During the "pioneering" period oxygen would be produced by processes that are easiest to employ (e.g. by ilmenite/glass reduction or carbothermal reduction). However, the oxygen yields will be relatively low. During the later period of "permanent human presence" oxygen can be obtained with high yields per ton of regolith by the more complex processes of fluorination or pyrolysis. This can be combined with the production of useful metals and silicon. In-situ oxygen production on the Moon for life support should be considered in combination with propellants production due to the complexity of the processes and plant masses involved (see discussion below), which implies that only the production and utilization of large quantities of oxygen in the order of 100 tons or more per year seem to promise economic advantages.

For the production of propellants and life support consumables from the Martian atmosphere, three well known processes are considered:

- solid oxide electrolysis,
- SABATIER-process, and
- reverse water gas shift process

Due to the nature of the involved chemical processes different quantities of reagents and reaction temperatures are required. Only the production of oxygen by solid oxide electrolysis can be performed without reagents. The economic production of propellants and life support consumables on Mars appears to be critical if viewed only in the context of a single mission. The lifetime of a Martian propellant plant should be increased significantly (e.g. to several missions) and export of propellants to Mars orbit for the Earth return path should be included. Furthermore, the utilization of water ice (from permafrost) on Mars should be investigated as an alternative processing concept, although the accessibility of permafrost is speculative (this must be further explored) and restrictions for potential landing sites have to be taken into account.

Recommended ECLSS for the three scenarios of human exploratory missions. So far, the available ECLS functions/techniques are not sufficiently developed to meet the requirements of human exploratory missions. Investigations into advanced life support system technologies are required based on bioregenerative technologies, on supplementory physico-chemical technologies, as well as on natural resources utilisation completed by extensive investigations into environmental monitoring issues. An appropriate combination of all these techniques will be necessary to ensure safe and successful interplanetary human missions and to ensure that human outposts on extraterrestrial bodies will become possible. For each mission scenario a tailored ECLSS should be developed as follows:

Scenario 1 : Lunar outpost at the south pole. With regard to the human needs of mission scenario 1, the transfer vehicle(s) required for the transfer Earth to Moon and back to Earth again (only 3-5 days transfer phase onboard a spacecraft) should only be equipped with conventional life support systems which have all consumables available necessary to keep the crew alive during the transfer phases including required back-ups. A BLSS is not adequate. If the lunar base is foreseen as a permanently equipped and inhabited set-up and not only for a single 180 days mission, the ECLSS of the base must be able of running continuously without shutdown and restarting when a new crew arrives. This makes high demands on the long-term stability and reliability of all systems. It is advantageous to close the ECLS loops to the extent possible with regard to the atmosphere, and, even more important, with regard to water, even though the regular transport capacity would allow to replace quite a lot of necessary consumables.

The proximity of the Earth allows a step by step setting-up of the base and its ECLSS, thereby reducing the costs of launching a complete and autonomous ECLSS at once. The ECLSS of a lunar base could be established in two phases:

- In the first phase, recycling of the atmosphere and of water should be achieved by conventional physico-chemical techniques which will stepwise be complemented by bioregenerative methods (algae as oxygen producers and CO_2 consumers for the management of the atmosphere; biological water treatment systems, e.g., crew waste by bacteria and perhaps fungi as a first step for the water regeneration/production, followed by a physico-chemical treatment depending on the usage of water (hygiene; drinking).
- In a second phase, food production facilities should be set-up including plant compartments (possible use of inflatable structures) with the possible use of direct sunlight.

At the end, the systems developed in these two phases will run together, algae being more manageable than higher plants for the control of the O_2/CO_2 balance, microbial and fungi compartments being necessary for the recycling of inedible biomass produced by plants. Hence, the moon is a perfect location to test and evaluate complex systems without major safety issues.

Scenario 2 : 1000 days Mars mission. Consdiring the enormous human needs for a mission to Mars, it becomes clear that the transfer vehicle(s) as well as the outpost station should be equipped with ECLSSs that are capable of recycling as much of the waste products as possible in order to keep the transport mass from Earth to Mars as low as possible. For the stay time on Mars it is strongly recommended to use the natural resources of the planet to the highest extent possible. There should be a strong link between a potential ISRU/ISPP plant and the ECLSS on a Mars base. Because it is planned to split the crew with 2 members remaining in Mars orbit and 4 landing on Mars, it is necessary to develop two autonomous life support systems which could work together during the transfer phases.

During the interplanetary transfer phase, the life support system must be able to sustain a crew of 6; in addition this is required for the crew of 2 remaining in Mars orbit. At least, the system must be able to recycle the atmosphere and water, thereby reducing the mass of consumables by 90%. The most probable biological systems involved are algae and microbial reactor – similar to those recommended for the first phase at the lunar base -, because of their relative small size, their dynamic response time, the possibility to control them and to restart the system relatively fast (2 – 3 days) in case of failure.

Higher plant could be used, depending on the area available (one has to keep in mind that an area of about 15 m^2 is the minimum requirement for a monoculture needed for feeding 1 person, however, that probably this would extend to an area of 30-40m^2). In the spacecraft, higher plant would be introduced only as a provider of fresh food to complement the diet (up to 20-30% of the diet). A BLSS could then recycle about 100% of oxygen and water and provide 30-40% of the food (including higher plants and algae a complement to the diet).

The long total stay on Mars of 525 days with nearly Earth-like day/night cycles make it desirable to develop bioregenerative technologies which support the physico-chemical ECLS components and vice versa, in particular with regard to water recycling and to on site food production. The required consumables for the return mission from Mars to Earth may be produ-ced in the Mars station by biological processes and by ISRU/ISPP processes.

There are two options for the ECLSS on the Martian outpost:

- the system is completely integrated in the landing module and is operated since the beginning of the mission. In this case it represent the 2/3 of the system presented above; or
- the system will be partially developed on the surface of Mars, and the landing module possesses only “classical” (storage/physico-chemical) systems. This second option has the advantage of reducing the requirements for the design of the landing module. On the other hand it requires:
  - structures on Mars ready for the development of the ECLSS (e.g., material, inflatable structures) that are previously installed (cargo….).
  - start up a biological life support system which can quickly reach a steady state. Unicellular organisms are the most probable candidates for starting such a system, which can be complemented further by higher plant for food production (plants or seeds coming from the spacecraft and planted on Mars).

Scenario 3 : 500 days Mars mission. Whereas during the transfer phase, the requirements on the ECLSS are similar as in scenario 2, in this case the 4 crew members stay only 30 days on the surface of Mars. Therefore, during the transfer phase, the life support system can be similar as in scenario 2.

The stay time on Mars is rather short, so that the decision whether to use an ECLSS with a high degree on loop closure (technically complicated with all its consequences) or to provide a simple, robust ECLSS working mainly with consumables, needs to be evaluated in more detail, which cannot be done in the frame of this study. In particular, the size/capacity of a electrical power production plant on the surface of Mars drives the design of an appropriate ECLSS. As a first estimate it is anticipated that a simple non-regenerative ECLSS has more advantages (simple, very mature technology available, reliable, etc.) than disadvantages due to its higher overall mass when compared with a regenerative ECLSS.

Roadmap for a Future European Strategy in Life Sciences and Life Support Systems towards Human Exploratory Missions, Precursor Studies and Terrestrial Applications and Benefits

This study has concentrated on the needs for R & D activities to sustain human health, wellbeing and efficiency on a long-term interplanetary mission, either to a lunar base or to Mars. Therefore, the roadmap is restricted to human-related aspects within a future European strategy. In order to occupy an active role in future human exploratory missions in the fields human health issues and life support systems, it is recommended that ESA should set up a R & D program that aims at

- fostering those fields in life sciences and technology where Europe has reached a competitive and leading role;
- coordinating all European efforts in thes fields, including those of its member states;
- strengthening European competitiveness by a stronger coordination of its space activities with terrestrial activities at regional and European level
- establishing synergies with terrestrial technology.

Lessons learned from the experience gained on the ISS may help Europe to increase its responsibility and visibility in future large international space projects.

Within the roadmap it is recommended to ESA to undertake the following steps:

- using forthcoming space missions which include
  - utilization of the ISS or other human missions in LEO;
  - utilization of robotic precursor missions orbiting the Moon or Mars
  - utilization of robotic precursor missions landing on the Moon or on Mars
- using terrestrial test beds and simulation facilities which include
  - heavy ion accelerators for radiation issues
  - isolation-confinement simulations, Antarctica - underwater - off-shore habitats, and bed rest facilities and modelling for gravity and psychological issues
  - laboratory facilities and habitable closed chamber with ALSS

Further details of the roadmap are given in Figures 1 to 7.

Synergism with terrestrial industry and applications

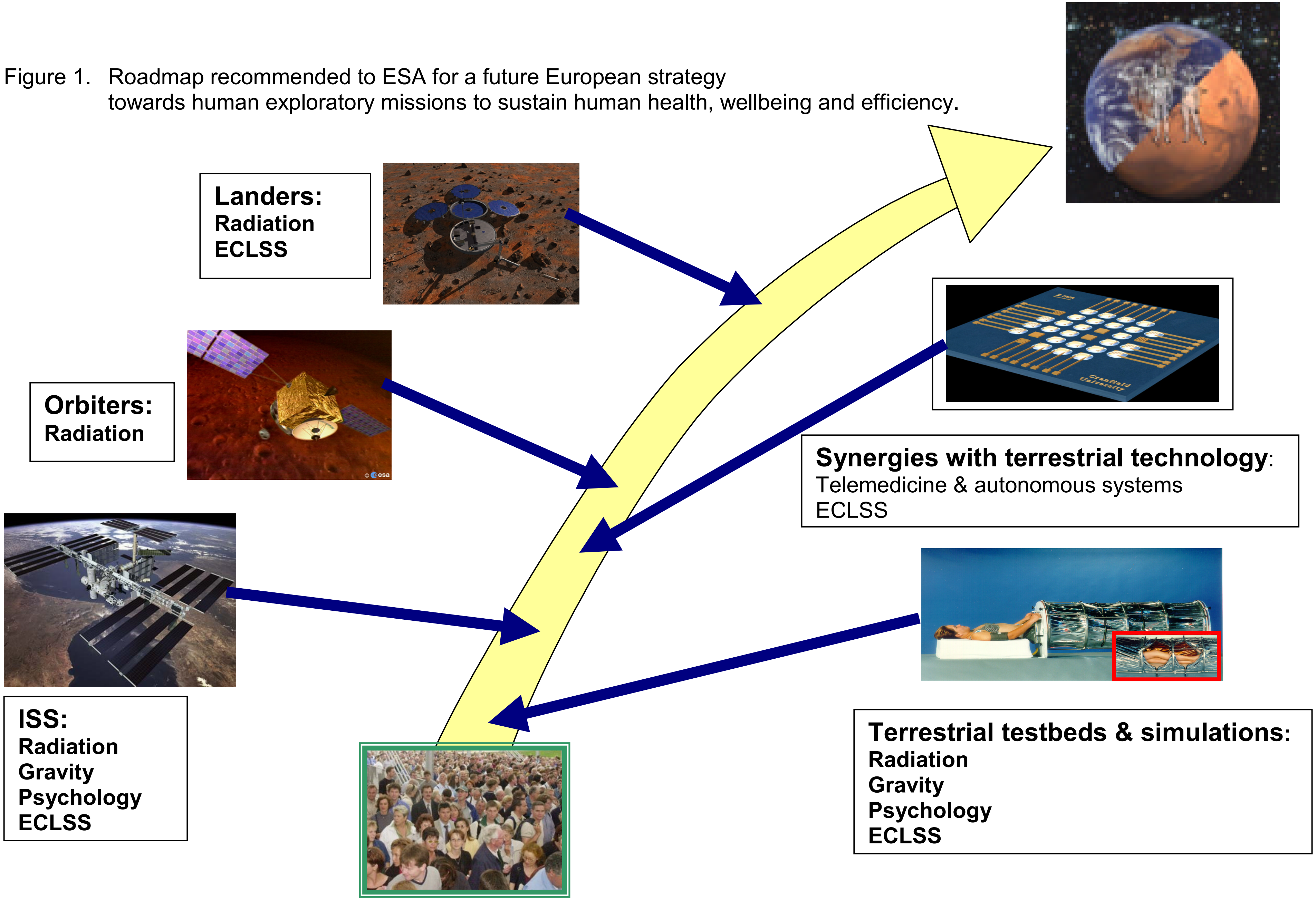
The special needs connected with humans in space and the responsibility for their health, wellbeing and reliability in performance, on the one hand can be a driver of technological development, on the other hand they may benefit from the fast development of terrestrial technologies, especially in information technology, communication, biodiagnostics and biosensorics and their miniaturization. Figure 8 indicates several examples of synergies with terrestrial applications, such as applications in health care, psychological issues and Advanced Life Support Technologies.

Conclusions

Based on experience from previous studies on human missions in LEO, -especially within the last two decades - the European scientific and technology community has gained substantial experience and achievements in assessing the risks for humans in this space environment, especially in view of assessing the radiation hazards and the adaptation to µg, as well as in the development of advances life support systems. This knowledge is a solid base when approaching the next frontier, namely human missions beyond the Earth orbit, i.e. to the Moon or to Mars. Whereas this means additional challenges to radiation protection and human physiology issues, other partially new areas of research and technology enter the field, such as psychological issues, ALSS with bioregenerative life support systems, autonomy in health and environmental control.

In order to be a competitive partner in a future enterprise of human exploratory missions, Europe should use all its potential for preparatory studies, including the use of the ISS and other satellites in Earth orbit, robotic precursor missions orbiting around or landing on Moon or Mars, and terrestrial test beds and simulation facilities. Experience has shown that unusual challenging conditions as given by the human exploration of space, induce a kick in technology development. It is expected, that when Europe takes an active part in the preparation of human missions to the Moon or to Mars, this decision will also mean a substantial contribution towards the competitiveness of European industry.

Figure 1. Roadmap recommended to ESA for a future European strategy towards human exploratory missions to sustain human health, wellbeing and efficiency.



Landers:
Radiation
ECLSS

Orbiters:
Radiation

ISS:
Radiation
Gravity
Psychology
ECLSS

Synergies with terrestrial technology:
Telemedicine & autonomous systems
ECLSS

Terrestrial testbeds & simulations:
Radiation
Gravity
Psychology
ECLSS

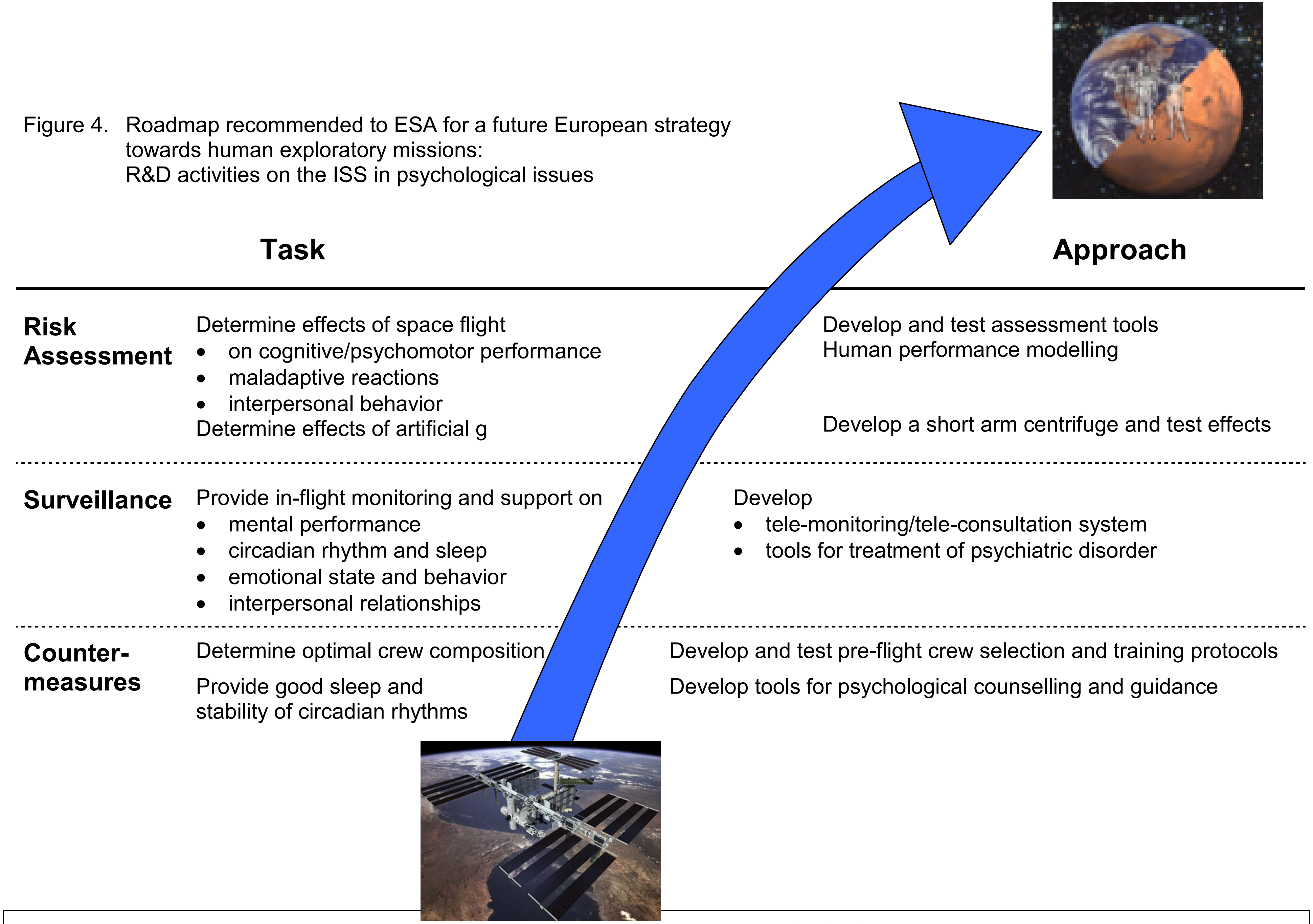
Figure 2. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities on the ISS for space radiation protection purposes

	Task	Approach
Risk Assessment	Determine depth dose distribution inside habitats and human body	Human phantoms inside and outside of ISS, e.g. MATROSHKA
	Determine interactions of space radiation and other space factors, e.g. µg	Cell and animal experiments with artificial radiation source
Surveillance	Determine personal biological significant radiation dose	Develop • personal dosimeters (passive and active) • biodosimetry concepts (e.g. chromosome aberration) • biodiagnostic systems (e.g. cellular biosensors)
Counter-measures	Determine role of diet in radiation responses	Interact with nutrition responsibles to develop dietary concepts for minimising oxidative stress

Figure 3. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities on the ISS for protection purposes from µg and low g effects

	Task	Approach
Risk Assessment	Determine mechanisms of µ/ g effects • on human health • on performance • on efficiency of medication	• Co-ordinated programme of integrated human physiology • Animal experiments • Pharmacokinetic studies • Mutation studies on microorganisms
Surveillance	• Provide a medical/surgical skill maintenance programme • Provide a health control system	Develop • telemedicine system • intelligent medical kits • compact diagnostic system with micro-/nanotechnology
Counter-measures	Control µg effects on human health Assess effects of periodical exposure to artificial g	Define criteria for designing and operating countermeasure systems for long-term µg exposure Develop and use a human short arm centrifuge

Figure 4. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities on the ISS in psychological issues



	Task	Approach
Risk Assessment	Determine effects of space flight • on cognitive/psychomotor performance • maladaptive reactions • interpersonal behavior	Develop and test assessment tools Human performance modelling
	Determine effects of artificial g	Develop a short arm centrifuge and test effects
Surveillance	Provide in-flight monitoring and support on • mental performance • circadian rhythm and sleep • emotional state and behavior • interpersonal relationships	Develop • tele-monitoring/tele-consultation system • tools for treatment of psychiatric disorder
Counter-measures	Determine optimal crew composition	Develop and test pre-flight crew selection and training protocols
	Provide good sleep and stability of circadian rhythms	Develop tools for psychological counselling and guidance

Figure 5. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities on the ISS for ECLSS development

	Task	Approach
P/C-LSS	Provide closed loop (air, O_2, water, waste) during Earth ↔ Mars transfer	Develop and test prototypes for regenerative LSS (e.g. for air revitalisation)
BLSS	Provide support to closed loop system (e.g., O_2, waste)	Develop and test reliability of supplementary systems (e.g., bioreactors, MELISSA)
	Determine genetic stability of BLSS	Study radiation/μg effects on BLSS functions
ECS	Provide integrated/modular environment monitoring and quality control system	Develop and test autonomous micro/nano-arrays
	Control microbial contamination	Develop feedback monitoring ↔ sterilizing procedures (e.g. DNA chips for monitoring)

Figure 6. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities on robotic precursor missions

	Task	Approach
Radiation protection	Determine space radiation scenario for a whole exploratory mission and its biomedical implications	Active radiation dosimetry systems on orbites and landers (e.g. radiation telescopes, RADEX)
BLSS	Determine habitability of Moon and Mars	Develop a small artificial ecosystem and install it on Moon or Mars (e.g., Photobioreactors)
	Determine utility of in situ resources	Test the compatibility of soil, light, atmosphere as natural resources for BLSS
ISRU	Determine the feasibility of O_2 processing concepts	Dvelop a test plant, installed on Moon and/or Mars (e.g. Sabatier process / water electrolysis)

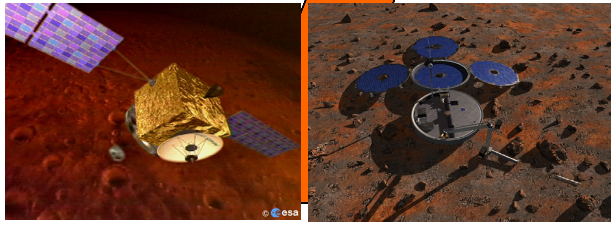


Figure 7. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
R&D activities using terrestrial testbeds / simulation facilities

	Task	Approach
Radiation protection	Improve and validate transport codes	Use heavy ion accelerators (e.g. GANIL, GSI)
	Determine biological effects of single heavy ions	Use microbeams from heavy ion accelerators
	Determine interaction of radiation with µg	Use fast rotation clinostate at heavy ion accelerator
µg / low g	Determine the adaptation of human body functions to long-term or repeated immobilization	Perform long-term and repeated bed rest studies
Psychology	Determine crew performance, interaction, maladaptive reactions in long-term confinement	Perform long-term studies in e.g., Antarctica, desert, underwater habitats, isolation chambers Perform Integrated Performance Modelling Environment
ECLSS	Determine the efficiency of environmental regulation of P/C-, BLSS in closed habitats	Install and test prototypes in habitable closed chambers
	Determine human health and environmental monitoring and quality control	Develop integrated/modular environment monitoring and quality control system by use of micro-/nanotechnology

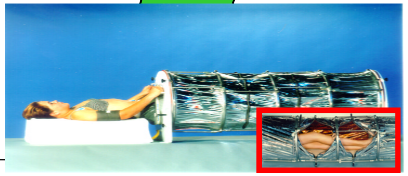
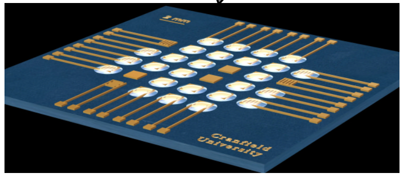


Figure 8. Roadmap recommended to ESA for a future European strategy towards human exploratory missions:
Synergies with terrestrial technologies / applications

	Space	**Terrestrial**
µg / low g, health care	Understanding the mechanisms if space induced disorders in e.g., • musculoskeleton • ageing Develop real time monitoring/autonomous diagnosis and therapy kits	• Monitor and prevent osteoporosis • Exercise programs for sedentary and elder population • Miniaturised kits for biodiagnostics • Telemedicine
Psychology	Develop integrated concept of specifi psychological coumermeasures	• Cope with stress situations • Integrated Performance Modelling Environment
ECLSS	Closed LSS Environmental monitoring and quality control	• Air and water management • Miniaturised kits for environmental diagnostics



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