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1 Rationale for European Participation in Human Exploratory Missions

1.1 Background

After the realisation of the International Space Station (ISS), human exploratory missions to the Moon or Mars, i.e. beyond Earth orbit, are widely considered as the next logical step in the human desire to expand. The ISS is the first example of an international cooperative venture for the joint development, operation and utilisation of a permanent space habitat in low Earth orbit (LEO), involving nearly all space-faring nations. Hence, with the ISS, a new era of peaceful cooperation in space on a global scale has started. Major partners are the USA, Russia, Japan, Europe and Canada, with the USA taking the leading role. Lessons learned from this experience may help Europe to increase its responsibility and visibility in future large international space projects.

If Europe plans to take an active role in future human exploratory missions, it should rely on the lessons learned from earlier human missions in Earth orbit (e.g., Spacelab, Mir), which were mainly performed bilaterally, as well as those from the current activities on the ISS. There are several fields in Life Sciences, in which Europe has a strong position, such as in human physiology and countermeasures, gravity biology, and radiation biology and dosimetry as well as in life support technologies.

In order to define its position in future human missions to the Moon or to Mars, ESA has initiated several activities:

- ESA had already set up a Lunar Study Steering Group in 1992, to investigate Europe's priorities for the scientific exploration and utilisation of the Moon (Balsiger et al., 1992). This was followed by an International Lunar Workshop in 1994 (Balsiger et al., 1994). Within the overall scenario of lunar exploration, the major life sciences needs were considered to be (i) the assessment of the boundary conditions for human safety, health, well-being and working efficiency at a lunar base (e.g., human physiology under reduced gravity, radiation protection and life support systems) with due consideration of the scientific as well as the operational aspects; and (ii) the establishment of an artificial ecosystem on the Moon, which could begin with a simple, remotely controlled system to be built up as the lunar base was developed.
- In 1998, ESA set up an Interdirectorate *Groupe de Réflexion* to investigate the role Europe could play in an international cooperative initiative for a human mission to Mars and to develop a plan to enable European participation in an international human exploration mission to Mars. It was recommended that, in the areas of human factor engineering, human physiology, radiation monitoring etc., which are already included in ESA's research plan for the ISS programme, research aimed at supporting, or preparing, for the human mission to Mars should be stressed. Within a strategy of human exploration of the solar system, the ISS has been identified as a mission benchmark.
- In 1998, ESA launched a study on the search for life on Mars (Brack et al., 1999) that, among other things, examined the ways in which a manned station on Mars might assist in further developing exobiology research on that planet and whether such a station would pose significant risks to the success of the search for life on Mars.
- In 2000, ESA initiated the HUMEX study in order to critically assess the adaptation of humans to interplanetary and planetary environments and their survival for long periods under such conditions. The results are presented in this report.

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- In 2001, ESA started the *Aurora* Programme, which aims to set out a strategy for Europe's solar system exploration over the next 30 years – and which also includes human expeditions to Mars. To reach these goals, Europe will have to agree on a realistic technological and scientific strategy, based on the experience in Europe and determined by the requirements of such an international enterprise.

Long-duration missions beyond LEO present tremendous human challenges. The HUMEX study has concentrated on human 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 put on human health care, well-being and performance (radiation effects, microgravity and reduced gravity, psychology issues and health maintenance) and on advanced life support developments.

1.2 Science aspects

There are four main drivers for human exploratory missions, science, technology, culture and economy.

The Moon's rich potential as a scientific outpost is based on three main areas that can benefit significantly from the presence of humans on the Moon (Balsiger et al., 1992; 1994):

- the science of the Moon, which includes geophysical, geochemical and geological research, leading to a better understanding of the origins and evolution of the Earth-Moon system;
- science from the Moon, which takes advantage of the stable lunar surface, its atmosphere-free sky and especially its radio-quiet environment, for astronomical observations, especially on the far side of the Moon; and
- science on the Moon with emphasis on studies of the stability of biological and organic systems under the hostile conditions, especially radiation, and the regulation of autonomous ecosystems (Horneck, 1996).

Mars is a major target in the search for life beyond the Earth. Dry river beds indicate that huge amounts of water and a denser atmosphere were present about 3 billion years ago. During this warmer and wetter period life may have originated on Mars and may even exist today in special "oases or ecological refuges" (e.g., geological formations below the surface with favourable conditions for life). The published, but controversial, discoveries of possible fossil life forms in martian meteorites may warrant optimism. Therefore the search for morphological or chemical signatures of life or its relics is one of the primary and most exciting goals of Mars exploration (Brack et al., 1999; Westall et al., 2000). In addition to exobiology, disciplines like geology, mineralogy, and atmospheric research play a central role in the scientific exploration of Mars. The general goal is to understand planetary formation and evolution processes including, if possible, the evolution of life. Mars is the planet most similar to Earth, and the question of climatic changes, especially the loss of water and atmospheric gases, is fascinating and relevant for understanding the Earth and may contribute towards understanding the evolution of the whole solar system. A number of items have been identified where human intervention could be beneficial to reaching the scientific goals, such as site identification by local analysis, sample acquisition at these sites, sampling and – if a laboratory is available on Mars – supervision of sample analysis (Brack et al., 1999).

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1.3 Technology aspects

The Moon is a suitable test bed for technologies to be applied in further space exploration initiatives, such as a Mars mission. Numerous aspects of the environments on the Moon and Mars are similar, above all the radiation field, thin atmosphere, reduced gravity, and dust. Even assuming a significant improvement in space technology in the coming years, intermediate steps, such as a human mission to the Moon, would be extremely useful in preparation for a journey to Mars. In addition, the Moon could be used for *in-situ* resource exploitation. There are indications that concentration and ore-formation processes have occurred on the Moon in the context of magmatic processes or due to the vaporisation of volatile elements during volcanism or impacts. Remote sensing with high spectral and spatial resolution as well as *in-situ* analyses (including drilling) are required for a better characterisation of potential lunar resources. It would be extremely fortunate for life support and propellant production if water could be found in permanently shaded craters as a relict of cometary impacts.

Meeting the scientific objectives of a Mars mission requires autonomous and intelligent tools, such as intelligent sample selection and collection systems. As soon as human travellers are involved, the need for integrated advanced sensing systems will become obvious, such as for biodiagnostics, medical treatment, and environmental monitoring and control. Furthermore, the development and test of technologies for *in-situ* resource utilisation, above all for producing propellant from atmospheric CO_2 or from water ice, but also for life support purposes will be a technology driver. A significant benefit is also expected from a human Mars Mission as a technology driver from which other space programmes could profit, e.g. by the development of a heavy lift vehicle, the improvement of propulsion systems, the use of extraterrestrial resources, advances in electrical power supply and closed life support systems as well as in automation and robotics.

It has frequently been observed that new and demanding situations require new technologies and thereby cause a push in technology development. Moving humans away from their home planet and establishing a new habitable environment on the Moon or on Mars would be such a new and demanding situation.

1.4 Cultural aspects

In the endeavour to explore the Earth, humans have crossed the seas, climbed the highest mountains, visited the poles, studied the depths of the ocean, and set up an artificial station in space orbiting the Earth. New frontiers have been opened in order to understand the unexplored. After having reached the most distant and hostile places on Earth it is a logical step to explore the neighbourhood of the Earth: the Moon and the terrestrial planets.

The Moon, as natural companion of the Earth, has substantially shaped the conditions on the Earth to make it a habitable planet and to sustain a biosphere. It can also be considered as a natural space station orbiting the Earth. Hence, human missions to the Moon, by establishing a first habitable outpost beyond the Earth on a natural body of our solar system, will be important cultural events for mankind. Changing our view from a geocentric to a more universe-oriented one may also contribute to solving local conflicts. Broadly stated, a human Moon mission would meet the natural human need to explore and expand to new regions. Once relatively economic access to space becomes available, space

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tourism will become a major business. A lunar base for scientific and technology purposes might also develop into an attractive object for tourism.

Of the terrestrial planets, Mars is by far the most attractive. When the first telescopes were directed towards Mars, channels and shaded areas were interpreted as huge agricultural plantations or lichens covering the surface. This latter conception was not ruled out until the two Viking spacecraft landed on Mars in 1976 and encountered a hostile and chemically highly reactive surface. But Viking and the follow-on missions also told us that the early Mars had probably experienced a similar climate to that of the early Earth, when life started here. Hence, Mars has been considered as a suitable and attractive target for terraforming, e.g. by using modern techniques of planetary and genetic engineering (McKay et al., 1991).

The benefits of exploratory missions as drivers in science and culture have been well described by M.E. DeBakey (2000): "We know from earliest recorded history, some 5000 years ago, that human beings have always sought to learn more about their world. The century just ended has witnessed stunning advancements in science and medicine, including the launching of space exploration. There is a danger, however, that the new century may usher in an age of timidity, in which fear of risks and the obsession with cost-benefit analysis will dull the spirit of creativity and the sense of adventure from which new knowledge springs".

1.5 Economic aspects

Mars and the Moon offer a wide variety of natural resources, which could be used for the production of propellants as well as in the design of advanced life support systems sustaining human settlements. Using these resources available on the planet or the Moon, would significantly reduce the costly re-supply requirement from Earth.

Mars provides a thin CO_2 atmosphere as well as water deposits in the polar regions and in the upper layers of its soil (permafrost), which could be used for an oxygen and water production plant. The Moon's regolith consists of up to 50% of chemically bound oxygen, which could be used for the establishment of a lunar oxygen production plant.

Furthermore, the Moon and Mars contain material that may become a desired target of exploitation for the benefit of life on Earth. An example is the relatively large ^{3}He resources on the surface of the Moon, which are generated by continuous bombardment of the lunar surface by the solar wind. ^{3}He is a valuable source used for nuclear fusion reactors, which are considered as one of the acceptable solutions to long-term energy demands of the population on Earth. Actually, thermonuclear fusion has been considered as one of the very few environmentally acceptable options (fusion, fission or solar) for providing useful and plentiful energy to mankind. Although the lunar soil contains only 13 mg/ton of ^{3}He down to a depth of about 5 m, calculations have shown that the lunar resources of ^{3}He would be sufficient to cover the energy needs on Earth for several centuries (Balsiger et al., 1992).

1.6 European competitiveness

Since its major involvement in Spacelab 1, Europe has built up a level of knowledge and experience in space life sciences that provides a solid foundation

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for a future involvement in human exploratory missions to the Moon or to Mars. Europe has, in particular, achieved a competitive position in human physiology and countermeasures, gravitation biology, radiation biology and dosimetry, as well as in life support technologies, as has been recently documented by the European Science Foundation in an assessment of ESA's Life Sciences Programme (ESSC-ESF, 2001). However, it is also worth mentioning that, within this ESSC-ESF-assessment, it has been stressed that those involved in the planning must move quickly if Europe is not to lose the leading role it is currently playing in the above mentioned fields of research.

Synergies with terrestrial applications are expected in various fields. An example is given by the competitiveness of the European biodiagnostic industry, which may be reinforced by the needs for developing and adapting diagnostic and therapeutic techniques for an interplanetary mission which require miniaturisation, autonomous health control systems and/or telemedicine systems.

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2 Reference Scenarios for Human Exploration

2.1 Introduction

Since the HUMEX study concentrates on human health issues during exploratory missions, and not the development of appropriate mission scenarios, the reference scenarios used in this study have been selected from existing plans, such as the NASA reference mission to Mars (NASA, 1997) or the ESA Space Exploration and Utilisation Study (ESA, 1998). The selection criteria were:

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

Table 2.1 lists the three reference scenarios selected for this study, with the Moon as target for one mission and Mars for two different missions. Each scenario involves different requirements for life sciences and life support systems, such as the degree of closure of the life support system (LSS) cycles, the need for radiation protection, countermeasures to limit microgravity or low gravity effects, and psychological issues. Therefore, in the following, a timeline is described for each scenario concerning:

- radiation exposure (in LEO, in interplanetary space, on Mars or on the Moon);
- gravity levels (microgravity during the lunar or interplanetary transfer, reduced gravity on the Moon and Mars, propulsive acceleration during launch, deceleration during landing and aerocapture);
- extravehicular activities (EVAs) on the Moon or Mars (including rover activities on planetary surfaces).

Table 2.1: The three reference scenarios selected for the HUMEX study

Mission	Target	Description
Scenario 1	Moon	lunar outpost at the south pole (constant sunlight and potential water ice deposits are assumed)
Scenario 2	Mars	A 1000 day Mars mission with long term stay on Mars (*in-situ* resource utilisation might be required)
Scenario 3	Mars	A 500 day Mars mission with short term stay on Mars

2.2 Scenario 1: lunar outpost at the south pole

The Moon is only about three days travel away from the Earth, whereas the journey to Mars will take a considerably longer time. Even assuming a significant improvement in space technology during the coming years, intermediate steps, such as a manned mission to the Moon, would be extremely useful in preparation for a journey to Mars. Hence, the Moon may be considered as a test bed for technologies to be applied in further space exploration initiatives, such as a Mars mission. In addition, the Moon could be used for *in-situ* resource exploitation.

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A transfer flight between the Earth and the Moon typically lasts from 3 to 5 days, depending on the selected launch window and propellant consumption. The Earth departure orbit should have an inclination of about 23.5°, which corresponds well to the plane on which the Moon orbits the Earth. On arrival at the Moon, a polar orbit has to be selected in order to minimise the Δv-requirement for the landing at a south pole base. Neglecting the Earth to LEO launch, the total Δv-requirement for a round-trip between LEO and the lunar surface amounts to about 9 km/s with an aerocapture manoeuvre for low-Earth-orbit insertion on arrival at the Earth. An aerocapture manoeuvre takes advantage of the upper layers of the Earth's atmosphere to decelerate a spacecraft, by atmospheric drag, from its hyperbolic velocity down to LEO orbital velocity (in contrast to aerocapture, aerobraking decelerates a spacecraft which is already in the gravity field of a planet, to achieve a lower orbit or landing, such as was carried out in the Mars Global Surveyor and Pathfinder missions). Aerocapture and aerobraking therefore represent crucial technologies to significantly lower the Δv-requirement, and lead to considerable mass and cost savings. However, these manoeuvres are very risky (especially aerocapture, which has not yet been done) and decrease the overall mission reliability. Taking into account that a lunar round trip requires a Δv of about 9 km/s and assuming that all spacecraft are equipped with a conventional chemical oxygen/hydrogen propulsion system, comprehensive spacecraft calculations indicate that two spacecraft are sufficient to carry out the transportation tasks.

The lunar south pole was selected as the site for a base because it offers permanent sunlight. This significantly simplifies the design of the electrical power system (especially the power storage system) and leads to considerable mass and cost savings compared to a lunar base around the equator where 14 days of sunlight alternate with the same period of absolute darkness. The lunar base should take advantage of an *in-situ* resource (e.g. oxygen) utilisation plant. It would be extremely fortunate, for life support and propellant production, if water could be found in permanently shaded craters as a relict of cometary impacts. Characterised by technologically challenging environments (e.g. extremely low temperatures), those craters are also interesting locations for science instruments which require cooling (e.g. for infrared-astronomy) or for propellant storage. Nearby mountains that are almost permanently illuminated by the Sun could be ideal locations for establishing a permanent lunar infrastructure.

In the beginning, the lunar base will be small (1 habitation module and 1 laboratory module with corresponding scientific and operational infrastructure) and should be compatible with an enhanced Ariane-5 launcher or Space Shuttle cargo bay. Figure 2.1 shows an artist's view of an extended lunar pole base which already consists of four modules

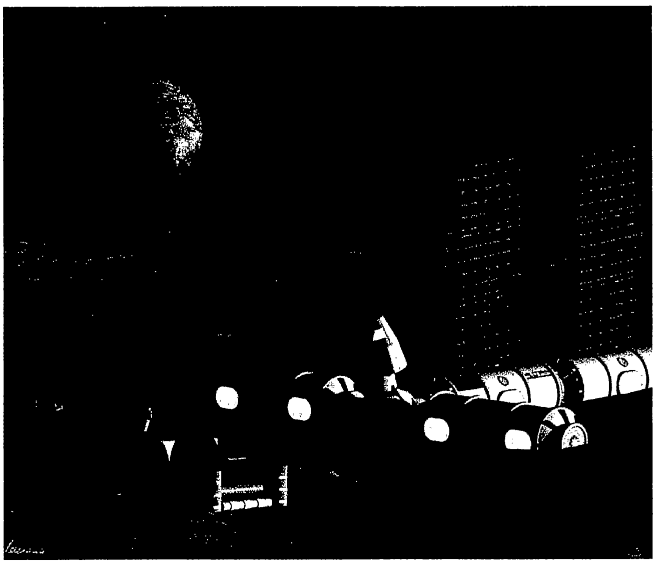

Figure 2.1: Artist's view of a lunar pole base with four modules (from www.alltra.de)

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(habitation and laboratory) and a crew rescue vehicle, which is docked to a connection node and would allow an emergency return back to the Earth within 24 hours.

The size of the crew should, on the one hand, be as large as possible, to achieve maximum mission safety and scientific and technological return, but is, on the other hand, the most important driver for the complexity and therefore for the total mass and programme cost. Positive experience has been gained during the Apollo programme with a crew size of three. However, almost all Apollo astronauts had Air Force training. Due to the fact that the manned lunar programme in this study concentrates mainly on scientific and technological objectives, the focus of the crew education should be more on scientific and technological issues. This should include skills in biology, medicine, geology, and/or astronomy. Furthermore, the following technological skills are essential for a safe and reliable operation of a lunar programme: commander, spacecraft engineering, manufacturing technology, and software engineering. Assuming that each crew member is intensively educated in one scientific and one technological area, this leads to a crew size of four members, which will be substituted every six months by supply flights from the Earth. Depending on the specific objectives of future 180-day missions, the crew's mix of skills can be adapted to the individual requirements of each mission.

Different radiation levels are experienced during a lunar roundtrip (Figure. 2.2). Before injection towards the Moon, the crew stay in LEO for three days, to get prepared for the trajectory, and are exposed to radiation doses typical for that orbit. Higher radiation levels occur during the Earth-Moon round trip (each flight is about 3-5 days) and slightly reduced radiation levels during the 180 day stay on the lunar surface, due to the partial shielding by the Moon itself. Radiation exposures caused by solar particle events are not considered in this profile. A more detailed description of the radiation exposure will be given in Section 4.2.

High g-loads (up to 3g) characterise the launch, the injection manoeuvres from LEO or low lunar orbit (LLO) into the trajectory and the ascent from the Moon, but they only last for about ten minutes (Figure 2.3). During the aerocapture manoeuvre on arrival at the Earth, the gravity level can reach values up to 6g, depending on the atmospheric drag and the density of the upper layers of the Earth's atmosphere, whereas the descent from LEO to the Earth in a Space Shuttle gives between 1g and 2g. Microgravity governs the Earth-Moon roundtrip. On the Moon the gravity level is about 1/6g.

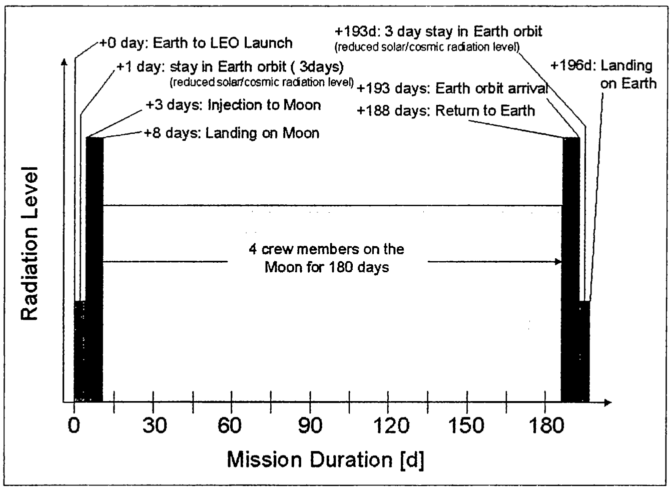

Figure 2.2: Profile of radiation levels experienced during a lunar roundtrip mission.

Due to the fact that EVAs are crucial for research work on the Moon, their number should be maximised. However, the LSS of an EVA-spacesuit requires substantial quantities of supplies, such as water for cooling, which are not recovered. Furthermore, airlock gas losses (volume 2 m^3)

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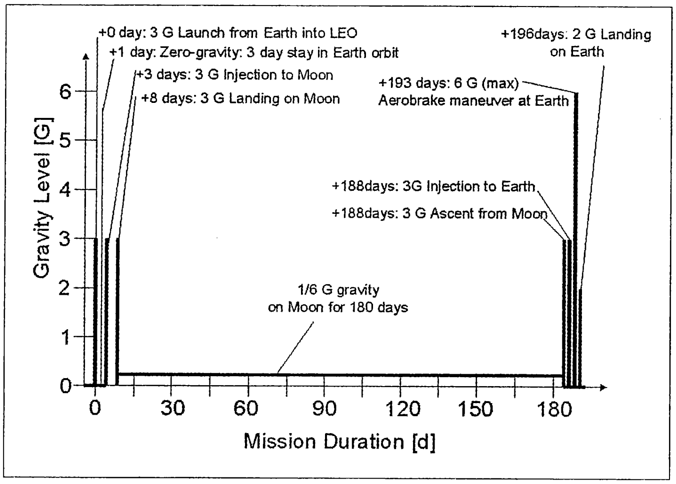

Figure 2.3: Profile of gravity levels experienced during a lunar roundtrip mission.

have to be considered when the crew leaves the base for an EVA. As a compromise between the number of EVAs desired and the allowable LSS-resources, we assume one EVA of two astronauts every three days. Because the capacity of the portable EVA-LSS is limited, the maximum duration of one EVA is assumed to be eight hours. A lunar oxygen production plant would allow more EVAs. EVAs are not foreseen during the transfer between Earth and the Moon. Table 2.2 summarises the crew activities for one lunar roundtrip.

Table 2.2: Main crew activities during one lunar roundtrip

Mission phase	**Earth-Moon transfer**	**Stay on the Moon**	**Moon-Earth transfer***	**Total mission**
Duration (days)	8*	180	8	196
Crew size	4	4	4	4
EVA number**	0	60	0	60

* including three days in LEO;
** each EVA includes two astronauts for eight hours maximum.

2.3 Scenario 2: 1000 day Mars mission with long-term stay on Mars

A Mars exploration scenario lasting 30 years could be divided into three main phases: a robotic phase at the beginning, followed by a robotic phase with local resource utilisation, and finally a human mission (ESA, 1998). Each phase should not be strictly limited in time, e.g., robotic activities will presumably continue during the human mission phase in order to support human life and operations on Mars.

For the purpose of the HUMEX study, a conventional spacecraft design, consisting of four elements, is foreseen for the human mission:

- an injection stage,
- an interplanetary parent ship (for the two interplanetary flights to and from Mars),
- a Mars lander habitat module, and
- a Mars ascent stage (to return to the parent ship, waiting in Mars orbit).

Each spacecraft element will have human control and access during all mission sequences. In an emergency during the flight towards Mars, the crew can break

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off the flight and find a backup habitat in the lander habitat module, which is designed to accommodate the crew for several hundreds of days (comparable to the lunar lander module which ensured the survival of the Apollo 13 crew). After Mars arrival, four crew members descend to the martian surface where they stay for 525 days, and two crew members remain in Mars orbit for the same period of time (comparable to the Apollo programme with one astronaut staying in lunar orbit while two astronauts descended to the lunar surface). The main reason for two crew members remaining in Mars orbit is safety. The astronauts in Mars orbit have to monitor and control the parent ship to ensure a safe return to Earth at the end of the mission. In view of accidents observed on the Mir space station and technology problems occurring with the first ISS modules, it is not expected that the parent ship could be kept in a workable condition for more than 500 days without human presence and support. The two astronauts in Mars orbit can also provide significant support to their colleagues on the martian surface, e.g., by remote sensing activities and communication services. However, these two astronauts will be subjected to considerable strain and stress, because they spend almost 1000 days in a microgravity environment within the limited volume of the parent module. Artificial gravity might be a useful solution to lower the strain of the entire crew, but this would increase spacecraft mass and costs by about 10 % (Boeing, 1991).

Compared to a lunar mission, a Mars mission represents a long duration undertaking. Depending on the selected interplanetary transfer trajectory the total mission duration ranges between 500 days (fast, high energy transfer) and 1000 days (slow, minimum energy transfer) (Reichert et al., 1999). A suitable launch window opens only about every 26 months, for several weeks.

In a 1000 day mission profile, the flight to Mars lasts typically 200 to 300 days. After arrival at Mars, the crew have to stay there for 400 to 500 days until the next low energy launch window opens again to return to Earth. The use of a low energy transfer trajectory is essential to significantly reduce the spacecraft's mass and therefore the total programme cost. The return flight again lasts 200 to 300 days, depending on the selected launch date (Figure 2.4). For the HUMEX study, the low energy launch window in 2018 has been taken as reference (Table 2.3).

Crew education should focus on scientific (e.g., biology, medicine, psychology, geology, atmosphere, meteorology, and astronomy) as well as technological skills (commander, spacecraft engineering, manufacturing technology, navigation, communication, software engineering). Assuming that each crew member is intensively educated in one scientific and one technological area, this leads to a crew size of six. For a lunar mission, the illness of one crew member does not directly jeopardise the mission safety, thanks to the relatively good transportation and communication opportunities. For a Mars mission, however, a serious illness of one crew member (e.g. the medical doctor) can jeopardise the whole mission due to the very long communication links (up to 45 minutes bi-directional) and transportation of several 100 millions of kilometres. It therefore appears important for the success of the mission that some crew members have a third back-up education in crucial skills like medicine, software and spacecraft engineering. This means that some or all crew members have be educated in up to three different scientific and technological areas.

The radiation levels experienced during a Mars mission are similar to those during a lunar roundtrip, with the exception that the time in interplanetary space with the highest radiation doses and risks of solar particle events is much greater, especially

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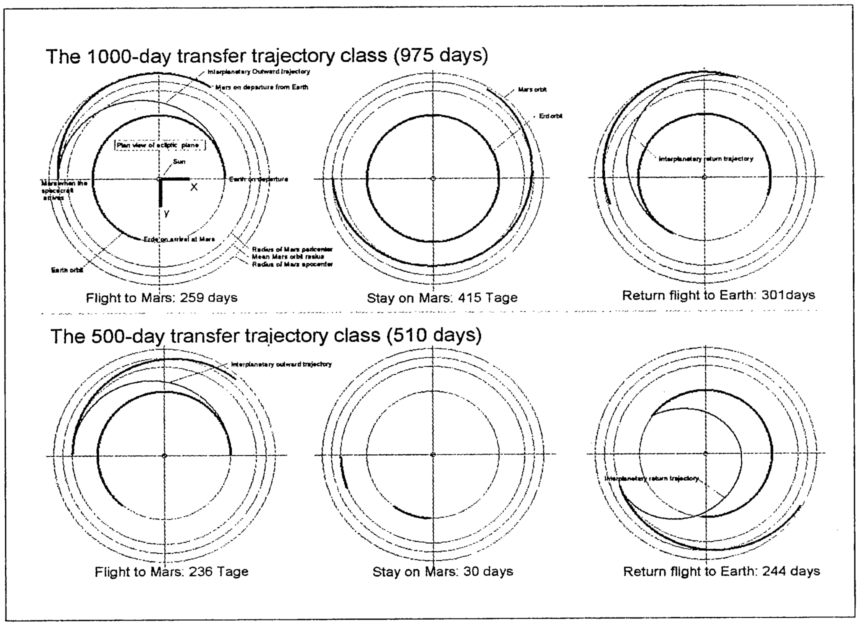

Figure 2.4: Earth-Mars transfer trajectories of the 1000 day and 500 day type human Mars mission (from Reichert, 1997)

Table 2.3: Sequence of mission Scenario 2, the 1000 day human Mars mission, and Scenario 3, the 500 day Mars mission.

Scenario 2 *Day*	**Scenario 3** *Day*	**Operation**
0	0	launch of the crew into LEO
1 - 7	1 - 7	Earth orbit (for seven days)
7	7	injection from LEO towards Mars
7 - 211	7 - 172	Earth – Mars transfer
211	172	Mars arrival
211 - 225	172 - 179	Mars orbit
225	179	landing on Mars (four crew members)*
225 - 750	179 - 209	Mars surface (four crew members)*
750	209	ascent from martian surface*
750 - 764	209-212	Mars orbit
764	212	injection from Mars orbit towards Earth
764 - 954	212 - 457	Mars – Earth transfer
954	457	Arrival and landing on Earth

* two crew members stay in Mars orbit

for the two astronauts remaining in Mars orbit (Figure 2.5). On the surface of Mars, additional shielding is provided by the thin atmosphere (see Section 4.2)

The injection manoeuvres from the Earth or Mars orbit and the ascent from Mars are characterised by gravity loads of up to 3g, lasting for about 10 minutes. Landing

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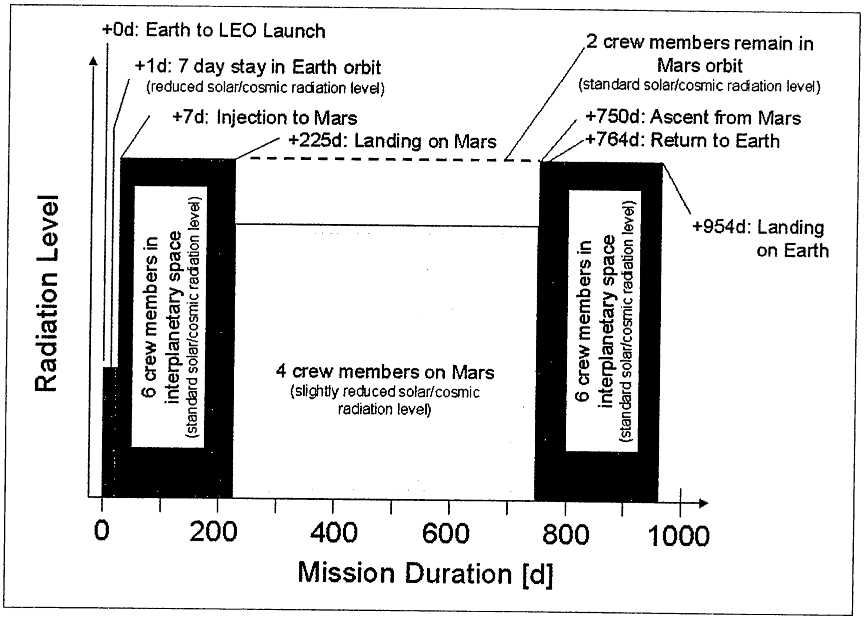

Figure 2.5: Profile of radiation levels experienced during a 1000 day Mars mission.

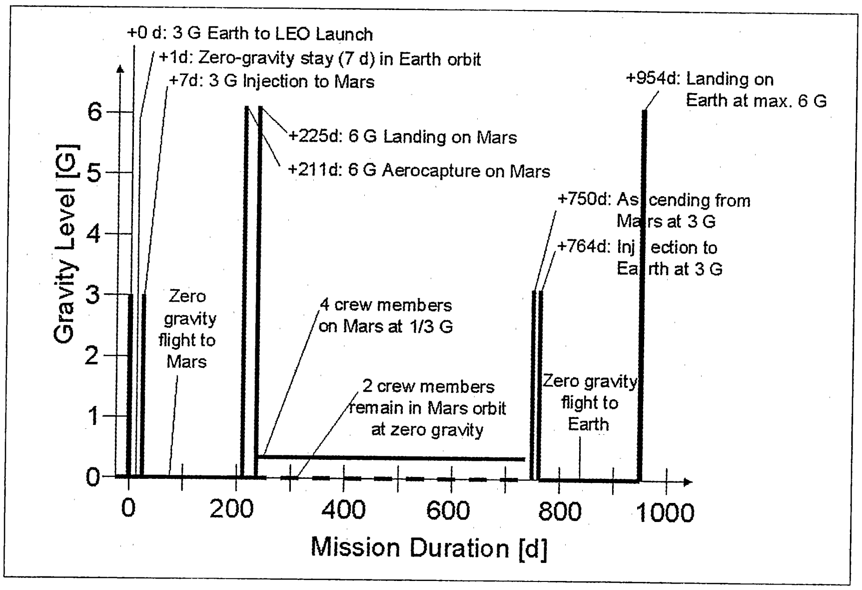

Figure 2.6: Profile of gravity levels experienced during a 1000 day Mars mission.

manoeuvres on Mars and the Earth are characterised by gravity loads up to 6g, due to the atmospheric drag. The interplanetary cruise is carried out in microgravity, on Mars gravity is 1/3g (Figure 2.6). Due to the fact that two crew members stay in Mars orbit, they have a cumulative microgravity duration of 947 days, interrupted only by orbit insertion at Mars (6g) and injection towards Earth (3g). In particular, the high gravity levels of 6g at Mars arrival (aerocapture) and landing on Earth (with a capsule) appear to be critical events for the health of the crew.

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Table 2.4: Main crew activities during a 1000 day Mars mission

Mission phase	Earth-Mars transfer*	Stay on Mars	Mars orbit	Mars-Earth transfer**	Total mission
Duration (days)	225	525	525	204	954
Crew number	6	4	2	6	6
EVA number***	0	175	0	0	175

* including 7 days in LEO and 14 days in Mars orbit;
** including 14 days in Mars orbit;
*** each EVA includes 2 astronauts for 8 hours maximum;

Table 2.5: Main crew activities during a 500 day Mars mission.

Mission phase	Earth-Mars transfer*	Stay on Mars	Mars orbit	Mars-Earth transfer**	Total mission
Duration (days)	179	30	30	248	457
Crew number	6	4	2	6	6
EVA number***	0	30	0	0	30

* including 7 days in LEO and 7 days in Mars orbit;
** including 3 days in Mars orbit;
*** each EVA includes 2 astronauts for 8 hours maximum, or 4 astronauts for 4 hours;

As for the lunar base, we assume on Mars one EVA by two astronauts every three days, each lasting for eight hours maximum. A martian oxygen and water production plant would increase the number of EVAs possible. EVAs are not foreseen during the transfer between the Earth and Mars. Table 2.4 summarises the crew activities for a 1000 day Mars mission.

2.4 Scenario 3: 500 day Mars mission with short-term stay on Mars

In a human mission with a crew of six on fast high energy trajectories, the flight to Mars typically lasts for 160-250 days (Figure 2.4). After the crew has landed, it stays on Mars for only 10 to 60 days. The return flight to Earth has to be carried out on a fast trajectory with a high Δv-requirement, which consumes a lot of propellant and leads to high spacecraft mass (Reichert, 1997). The high energy return trajectory intersects Earth orbit and can even reach the orbit of Venus. At Earth arrival, the hyperbolic velocity of the spacecraft can reach a level which requires an additional deceleration manoeuvre in order not to burn up the capsule during its entry into the Earth's atmosphere. A further disadvantage of the 500 day trajectory is that the Δv-requirement differs significantly for different launch windows. This makes it difficult to carry out several missions to Mars with the same spacecraft design, because the size and performance parameters of the spacecraft differ significantly from one launch window to another, due to significantly

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different propellant mass fractions. An advantage, however, is the low total mission duration of only about 500 days, which causes lower strains and stresses for the crew. For this reason, the 500 day mission to Mars has been selected as the third reference scenario in the HUMEX study and also in order to have a comparison reference to the 1000 day mission. Its mission sequence and profile are similar to those of the 1000 day mission (Table 2.3) with each element lasting just for a shorter time. The radiation and gravity levels are also similar. In order to make maximum use of the short stay on Mars we assume one EVA of two astronauts to take place every day for eight hours maximum. This could also mean that all astronauts can undertake an EVA for four hours every day (neglecting increased airlock losses). Table 2.5 summarises the crew activities for a 500 day Mars mission.

2.5 References

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3 Life Sciences and Life Support Requirements

3.1 Acceptable risks

Based on general human health statistics, the following safety objectives have been chosen for the HUMEX study:

- The individual risk of death from illness during the mission shall not be greater than 2 x 10^{-3}/year. This figure is taken from human health statistical tables (as used, for instance, by insurance companies), in which the individual risk of death from illness, the so-called "natural death", for a 30 to 60 year old person (of the general population in Western countries) is quoted as 2 x 10^{-3}/year.

- The individual risk of death by injury during the mission (excluding spacecraft failure) shall not be greater than 4 x 10^{-4}/year. This value is based on the value for the so-called "accidental death" of a 30 to 60 year old person (of the general population in Western countries). The baseline for terrestrial risk of death by both illness and injury is therefore not greater than 2.4 x 10^{-3}/year.

- The individual risk of death (from all causes, including spacecraft failure) shall be maintained during the mission at less than 3 x 10^{-2}/year. This value is based on that for the most exposed professions, such as fighter pilots, helicopter pilots, or astronauts.

Using the classical reliability requirements for human space missions (ESA, 1990; NASA, 1995), reliability objectives have been set for each mission scenario (Tables 3.1 and 3.2) In cases, in which the reliability requirement is unknown, the mission phase reliability requirements have been (arbitrarily) shared equally between the different mission phases.

Table 3.1: Estimated reliability objectives for Scenario 1, the lunar base mission

Mission phase	Launcher	Transfer vehicle, lander/habitat	Crew survival (illness or injury*)	Ground segment**	Overall mission reliability
Earth launch	0.99***	0.99712	~1	0.999987	
Earth-Moon transfer		0.99712	0.9999	0.999987	
Moon landing		0.99712	~1	0.999987	
Moon stay		0.99712	0.9953	0.999987	
Moon launch		0.99****	1	0.999987	
Moon-Earth transfer		0.99712	0.9999	0.999987	
Earth aerocapture		0.99	~1	0.999987	
Earth landing		0.99712	~1	0.999987	
Reliability goals	0.99	0.9633	0.9951	0.9999	0.949

* *spacecraft failure excluded;*
** *with communication system;*
*** *with crew escape system;*
**** *without crew escape system*

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For the lunar mission, with 180 days stay at the lunar base, the overall mission reliability objective is estimated to be 0.949 (Table 3.1). This value meets the acceptable risk requirements mentioned above; considering an individual risk of death of $\leq 3 \times 10^{-2}$/year, and four crew members during a 180 day (approximately half a year) mission, this would correspond to a required lunar base mission reliability of at least 0.941 ($=(1\text{-}0.03/2)^4$). The overall crew mission survival probability with regard to death by illness or injury (spacecraft failure excluded) is estimated to be 0.9951 (Table 3.1). This value also lies in the range of accepted risks: taking an individual risk of death by illness or injury of $\leq 2.4 \times 10^{-3}$/year would give, for the 180 day lunar base mission (four crew members), an accepted probability of death by illness or injury of 0.995 ($=(1\text{-}0.0024/2)^4$). As a consequence, for designing and sizing the crew health control system for a 180 day lunar base mission (Scenario 1), the probability of death by illness or injury (excluding spacecraft failure) for the whole crew should be $< 2 \times 10^{-4}$/year onboard the Earth-Moon transfer vehicle, and $< 4.7 \times 10^{-3}$/year onboard the Moon lander and habitable module. These values are compatible with the mission safety objectives presented above and will be taken as an input for the HUMEX study.

Similar reliability assessments are given for Scenarios 2 and 3 with Mars as the target (Table 3.2). For Scenario 2, the 1000 day Mars mission, the overall mission

Table 3.2: Estimated reliability objectives for Scenario 2, the 1000 day Mars mission (values for Scenario 3, the 500 day Mars mission are given in brackets, if different from Scenario 2)

Mission phase	**Launcher**	**Transfer vehicle, lander/habitat**	**Crew survival (illness or injury*)**	**Ground segment****	**Overall mission reliability**
Earth launch	0.99***	0.99712	~1	0.999988	
Earth-Mars transfer		0.99712	0.9914 (0.993)	0.999988	
Mars aerocapture		0.99	~1	0.999988	
Mars landing		0.99712	~1	0.999988	
Mars stay		0.99712	0.98 (0.9988)	0.999988	
Mars launch		0.99****	~1	0.999988	
Mars Earth transfer		0.99712	0.992 (0.9902)	0.999988	
Earth aerocapture		0.99	~1	0.999988	
Earth landing		0.99712	~1	0.999988	
Reliability goals	0.99	0.963	0.964 (0.982)	0.9999	0.919 (0.936)

* *spacecraft failure excluded;*
** *with communication system;*
*** *with crew escape system;*
**** *without crew escape system*

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reliability objective is assessed as 0.919. This value is much higher than that calculated from an individual probability of death (all causes mixed, including spacecraft failure) of < 3 x 10^{-2}/year which would only allow for an overall mission reliability (six crew members) of 0.5977 (=$(1-0.03 \times 1000/365)^6$). The overall crew mission survival probability with regard to death by illness or injury (spacecraft failure excluded) is assessed as 0.964. Assuming an objective of individual risk of death by illness or injury of < 2.4 x 10^{-3}/year would allow for an accepted probability of death by illness or injury of 0.96 (=$(1-0.0024 \times 1000/365)^6$). Therefore, for designing and sizing the crew health control system for the 1000 day Mars mission, targets, which are compatible with the mission safety objectives, of a probability of one death by illness or injury (excluding spacecraft failure) among the whole crew, are taken as input for the HUMEX study; i.e. < 1.66 x 10^{-2} for the Earth-Mars (and Mars-Earth) transfer and onboard the Mars orbiting vehicle, and < 2 x 10^{-2} onboard the Mars lander habitable vehicle.

For the 500 day Mars mission (Scenario 3), the overall mission reliability and the mission crew survival probability are slightly higher than for Scenario 2 (Table 3.2). In this case, the targets for a probability of death by illness or injury (excluding spacecraft failure) for the whole crew are < 1.7 x 10^{-2} for the Earth-Mars and Mars-Earth transfer and onboard Mars orbiting vehicle, and < 1.2 x 10^{-3} onboard the Mars lander habitable vehicle.

3.2 Life support needs

For human exploratory missions, the human requirements need to be specified in terms of spacecraft architecture (e.g., minimum volumes, privacy/personal needs, traffic flow, workstation needs, meeting/recreation needs, countermeasure needs, window and door integration), of quantity and quality of consumables (e.g., oxygen, food and beverages, drinkable water, water for personal hygiene, hygienic articles, clothing), of quantity and quality of waste production (e.g., solid matter including rubbish, liquids, gas contaminant production), and of quality control (e.g., of water and food). Based on presently available techniques used onboard existing spacecraft (NASA, 1994; ESA, 1994a; ESA, 1994c; Brown et al., 1990; NASA, 1985), the following assumptions have been made:

- all items and consumables required to satisfy human needs are carried from Earth;
- no recycling of the human wastes;
- average daily oxygen consumption is 1020 g/person (taking into account that the astronauts have to perform intensive physical training for two hours per day);
- two alternative body hygiene protocols are considered:
  - no shower (soap impregnated towels, wet and dry towels, dry shampoo, toothpaste and chewing gum) with a daily water need of 1800 g/person;
  - one shower/person per day with a daily water need of 23000 g/person.
- daily water requirement is based on
  - 2100 g/person drinking water
  - 700 g/person for food hydration
  - 1800 g/person for hygiene purposes (no shower, or
  - 23000 g/person for hygiene purposes (one shower/day)

  with a total daily water requirement of 4600 g/person (no shower) or 25800 g/person (1 shower).

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- water requirement for each EVA is 5000 g /suit assuming eight hours duration of EVA;
- food is composed of a mixture of freeze-dried, dehydrated food (daily ration (450 g + 800 g water)/person = 47% of the needs), and tinned food (1350 g/person = 53% of the needs);
- air needs for airlock manoeuvre are 4800 g/EVA (airlock volume ~ 4 m^3);
- human waste production has been rated according to:
  - vomits: four vomits/person and day for three days after planet launch and for two days after planet landing);
  - defecation: one defecation/person/day or 300 g/person/day; and
  - urination: five urinations/person/day or 1500 g/person/day;
- the weight of the personal kits is extrapolated from the presently used personal kits by increasing the weight according to the mission duration;
- the weekly need for changes of clothes is
  - three sets of underwear/person plus
  - one complete set of clothes (excluding underwear)/person plus
  - one sleeping bag/person for two weeks.

Based on these assumptions, the total quantities of life support items for the Earth-Moon-Earth transfers and Earth-Mars-Earth transfers, respectively, are given in Tables 3.3 to 3.5. The difference of weight between the needs and the wastes in Table 3.5. is explained by the weight of the personal kits (40 kg), which are counted in the needs but not in the wastes. Concerning Earth-Moon-Earth transfers, the requirements can be met by existing manned spacecraft (e.g., the Space Shuttle and Soyuz) whereas those for Earth-Mars-Earth transfers greatly exceed the capabilities of current spacecraft.

Table 3.3: Human needs and waste production of mission Scenario 1 (lunar base mission)

Needs and waste products	**Total amount for Earth-Moon-Earth transfers**		**Total amount for 180 days stay on the Moon**	
O_2	32.6	kg	734.4	kg
Air for EVA airlock manoeuvres			144.0	kg
Water (total needs):	147.2	kg	18876	kg
for hygienic purpose	57.6	kg	16560	kg
drinking water	89.6	kg	2016	kg
for EVA suits			300	kg
Food	85.4	kg	1922.4	kg
Unique items	62.3	kg	541.1	kg
Human metabolic waste				
CO_2	39.7	kg	892.8	kg
water vapour	94.4	kg	2124	kg
energy	462080	kJ	10396800	kJ
Other human waste				
Solid (faeces, packaging, towels, cloths)	67.1	kg	1509.1	kg
Liquid (urine, vomit, hygienic water)	92.4	kg	17209.6	kg

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Tables 3.3 to 3.5 also show the life support requirements for the stay on the Moon or Mars. Besides the additional weight of the personal kits, the difference between needs and wastes is due to air lost during airlock manoeuvres (144 kg) and water lost by EVA suit evaporators (300 kg). The requirements for the stay on the Moon as well as for the short 30 day stay on Mars might be partly met by the current human space stations (Mir and ISS), but only if the Mars surface spacecraft is designed just for a 30 day human exploration mission, and not as a first step towards a permanent human Mars base.

For the lunar base and for the long-term missions to Mars, potential mass savings might be achieved in the following areas: O_2/CO_2 recycling; H_2O recycling (from water vapour and liquid waste); a "towels + cloths" washing-drying system; a recycling packaging system for foods and unique items, and an "on-site" food production system (see Chapter 5).

Table 3.4: Human needs and waste production of mission Scenarios 2 and 3 (Mars missions)

	Scenario 2		**Scenario 3**	
Needs and waste products	**Earth-Mars-Earth transfers**	**525 days stay on Mars**	**Earth-Mars-Earth transfers**	**30 days stay on Mars**
O_2	3654 kg	2142 kg	2631.6 kg	122.4 kg
Air for EVA airlock manoeuvres		432 kg		72.0 kg
Water (total needs):	92416 kg	55080 kg	66564.0 kg	702.0 kg
for hygienic purpose	82386 kg	48300 kg	59340.0 kg	216.0 kg
drinking water	10030 kg	5880 kg	7224.0 kg	336.0 kg
for EVA suits		900 kg		150.0 kg
Foods	9563.9 kg	5607 kg	6888.6 kg	320.4 kg
Unique items	2673 kg	1581 kg	1915.7 kg	173.5 kg
Human metabolic wastes				
CO_2	4441.7 kg	2604 kg	3199.2 kg	148.8 kg
water vapour	10566.9 kg	6195 kg	7611.0 kg	354.0 kg
energy	51724080 kJ	30324000 kJ	37255200 kJ	1732800 kJ
Other human wastes				
solid (faeces, packaging, towels, cloths)	7507.9 kg	4401 kg	5407.7 kg	251.5 kg
liquid (urine, vomits, hienic water)	85615.8 kg	50192 kg	61668.0 kg	325.6 kg

Table 3.5: Summary of life support requirements for the three mission scenarios

Scenario	**Mission**	**Needs (kg)**	**Wastes (kg)**	**Energy (kJ)**
1	Earth-Moon-Earth	327.6	293.6	462080
	stay on Moon	22217.9	21736.6	10396800
2	Earth-Mars-Earth	108306.3	108137.4	51724080
	stay on Mars	64842.6	63395.2	30324000
3	Earth-Mars-Earth	77999.9	77889.6	37255200
	stay on Mars	1390.3	1080.1	1732800

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Table 3.6: Probabilities of occurrence of diseases and injuries during the three mission scenarios.

Description		Scenario 1		Scenario 2		Scenario 3	
	Incidence per person per year	Earth-Moon -Earth transfer	Stay on Moon	Earth-Mars -Earth Transfer	Stay on Mars	Earth-Mars -Earth Transfer	Stay on Mars
Intestinal infectious diseases	0.001	8.767E-05	0.00197	0.00981	0.00575	0.00705	0.00033
Non-zoonotic bacterial diseases	0.0002	1.753E-05	0.00039	0.00196	0.00115	0.00141	6.575E-05
Viral disease	0.001	8.767E-05	0.00197	0.00981	0.00575	0.00705	0.00033
Venereal diseases	0.001	8.767E-05	0.00197	0.00981	0.00575	0.00705	0.00033
Malignant neoplasms	0.0008	7.014E-05	0.00158	0.00785	0.00460	0.00564	0.00026
Endocrine, nutritional, metabolic, immunity (excludes dehydration)	0.003	0.00026	0.00592	0.02944	0.01726	0.02116	0.00099
Diseases of blood and BF organs	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Psychoses	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Neurotic disorders	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Inflammatory diseases of the CNS	0.0003	2.630E-05	0.00059	0.00294	0.00173	0.00212	9.863E-05
Epilepsy	0.0005	4.384E-05	0.00099	0.00491	0.00288	0.00353	0.00016
Migraine	0.0005	4.384E-05	0.00099	0.00491	0.00288	0.00353	0.00016
Disorders of eye and adnexa	0.04	0.00351	0.07890	0.39255	0.23014	0.28208	0.01315
Diseases of ear and mastoid process	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Cardiovascular disease	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Acute respiratory infections	4	0.35068	7.89041	39.25479	23.01370	28.2082	1.31507
Pneumothorax	0.0005	4.384E-05	0.00099	0.00491	0.00288	0.00352	0.00016
Dental disease	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Digestive disease	0.05	0.00438	0.09863	0.49068	0.28767	0.35260	0.01644
Nephritis, nephrotic syndrome, nephrosis	0.0002	1.753E-05	0.00039	0.00196	0.00115	0.00141	6.575E-05
Urinary calculi	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Cystitis	0.9	0.07890	1.77534	8.83233	5.17808	6.34685	0.29589
Disease of male genital organs	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Disorders of breast & female organs	0.05	0.00438	0.09863	0.49068	0.28767	0.35260	0.01644
Infections of skin and subcutaneous tissue	0.9	0.07890	1.77534	8.83233	5.17808	6.34685	0.29589
Arthropathies & related disorders	0.02	0.00175	0.03945	0.19627	0.11507	0.14104	0.00658
Dorsopathies	0.02	0.00175	0.03945	0.19627	0.11507	0.14104	0.00658
Symptoms & ill-defined conditions	10	0.87671	19.72603	98.13699	57.53425	70.5205	3.28767
Fractures of the skull	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Fracture of the spine & trunk	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Fracture of upper limb	0.006	0.00053	0.01184	0.05888	0.03452	0.04231	0.00197

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Table 3.6: (Continued)

Description	Incidence per person per year	Scenario 1 Earth-Moon -Earth transfer	Scenario 1 Stay on Moon	Scenario 2 Earth-Mars -Earth Transfer	Scenario 2 Stay on Mars	Scenario 3 Earth-Mars -Earth Transfer	Scenario 3 Stay on Mars
Fracture of lower limb	0.003	0.00026	0.00592	0.02944	0.01726	0.02116	0.00099
Dislocations	0.005	0.00044	0.00986	0.04907	0.02877	0.03526	0.00164
Sprains & strains	0.07	0.00614	0.13808	0.68696	0.40274	0.49364	0.02301
Head injury	0.002	0.00018	0.00395	0.01963	0.01151	0.01410	0.00066
Internal injury	0.0005	4.384E-05	0.00099	0.00491	0.00288	0.00353	0.00016
Open wounds	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Superficial injury	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Contusions	0.02	0.00175	0.03945	0.19627	0.11507	0.14104	0.00658
Crushing injury	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Foreign bodies	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Burns	0.01	0.00088	0.01973	0.09814	0.05753	0.07052	0.00329
Poisoning	0.002	0.00017	0.00395	0.01963	0.01151	0.01410	0.00066
Toxic effects	0.005	0.00044	0.00986	0.04907	0.02877	0.03526	0.00164
Radiation short term disease *	0.00001	8.767E-07	1.973E-05	9.814E-05	5.753E-05	7.052E-05	3.288E-06
Radiation long term disease (neoplasm induced)*	0.0008	7.017E-05	0.00158	0.00785	0.00460	0.00564	0.00026
Bone demineralisation (bone fracture risk if more than 15% on DEXA measurement)	0.8	0.07014	1.57808	7.850958	4.60274	5.64164	0.26301
Space adaptation syndrome (3 days duration)	0.009	0.00079	0.01775	0.088323	0.05178	0.06347	0.00296
Exercise capacity decrease (> at 20% / pre-flight, muscular and cardiovascular causes)	0.8	0.07014	1.57808	7.850958	4.60274	5.64164	0.26301
Orthostatic intolerance under x g (2 days after landing)	0.006	0.00053	0.01184	0.058882	0.03452	0.04231	0.00197
Effects of reduced temperature	0.005	0.00044	0.00986	0.049068	0.02877	0.03526	0.00164
Effects of heat and light	0.007	0.00061	0.01381	0.068695	0.04027	0.04936	0.00230
All causes and illness	17.88526	1.56741	35.26670	175.451855	102.86122	126.078	5.87778
Estimated mortality by illness	0.002	0.00018	0.00395	0.019627	0.01151	0.01410	0.00066
Estimated mortality by injury (excluding spacecraft failure)	0.0004	3.507E-05	0.00079	0.003925	0.00230	0.00393	0.00230
Estimated mortality by illness or injury (excluding spacecraft failure)	0.0024	0.00021	0.00473	0.023553	0.01381	0.01803	0.00296

* Standard limits respected

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3.3 Crew health control needs

The risk of occurrence of illness or injury during a mission have been estimated using a weighted compilation of epidemiological data derived from analogous hazardous situations, such as Antarctic winters, spaceflight, Polaris submarines, US Navy, offshore oil workers, and other public sources (ESA, 1994b). The incidence rates are treated with 95% confidence limits. Using the International Classification of Diseases, Table 3.6 summarises the probabilities of diseases and injuries for the three mission scenarios. For Scenarios 2 and 3, estimations for the two crew members orbiting Mars have been considered, together with the Earth-Mars-Earth transfer process, whereas for the stay on Mars estimations have only included the four crew members landing on Mars. The estimates, given in Table 3.6 are in good agreement with previous analyses of crew health issues during long-duration space flights (Kutyna et al., 1985; Sulzman et al., 1988).

3.3.1 Crew health control needs for mission Scenario 1, the lunar base mission

For mission Scenario 1, the lunar base scenario, the following space-related disorders should be noted (Table 3.6):

- There is a significant probability of diseases and injuries occurring during the 180 day Moon stay, with a lower risk during Earth-Moon-Earth transfers.
- Radiation exposure should be an accepted risk.
- Bone demineralisation during the lunar stay (1/6 of Earth's gravity) is not documented, but should be less than for equivalent microgravity exposure, i.e. less than the 15% threshold considered as the level of significant increase of bone fracture risk. It should be noted that a six month stay in microgravity resulted in a mean loss of ~11% in bone mass, but 23% in one case, at the worst body location, the pelvis (Oganov et al., 1992; Oganov & Schneider 1996; Daphtary et al., 2000). Therefore the risk of bone demineralisation during the 180 day lunar stay needs further investigation.
- The space adaptation syndrome and Moon or Earth sickness (after Moon and Earth landing) have to be treated for three days after Earth launch, and on Moon landing and Moon launch. Operational activities must be reduced during these periods, and EVAs must be avoided. The necessary medication must be available on board the transfer spacecraft and in the lunar base.
- Orthostatic intolerance occurring after Moon and Earth landing has to be monitored, and treated – if necessary – for two to three days after Moon and Earth landing. Operational activities should be reduced during these periods, and EVAs avoided. The necessary equipment and medication must be available on board the transfer spacecraft and in the lunar base.
- Exercise capacity should decrease during the lunar stay, but the magnitude required is presently not documented. The reduction should, however, be less than for an equivalent duration under microgravity (i.e. less than 20%). To minimise the reduction of physical work capacity a physical training facility (gymnasium) must be installed at the lunar base. The type and duration of exercise will need further investigation.

The potential disorders require that the medical equipment onboard the spacecraft and especially in the lunar habitat allow for the following:

- diagnosis and treatment of infectious and inflammatory diseases (e.g., respiratory, dental, skin, digestive, genito-urinary, arthropathies);
- diagnosis and treatment of psychological and psychiatric problems and all crew members should be trained to manage psychological issues;

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- treatment of hypertensive disease, heart ischaemia, haemorrhoids, urinary calculus, and peptic ulcers;

The medical equipment must include medical diagnostic equipment, ENT, eye and dental kits and related external medication as well as mini-surgery kits, immobilisation splits and medication for the treatment and management of minor injuries, such as sprains, strains, superficial injuries, local burns, and contusions. In the case of medical emergency situations (e.g., cardiac or cerebral strokes), serious injury (e.g., fractures, crushing, extended burns, or open wounds) and poisoning, the medical equipment on board must allow the stabilisation of the patient(s) and emergency return to Earth within some days. In any case, crew members with appendectomies should be preferred.

3.3.2 Crew health control needs for mission Scenario 2, the 1000 day Mars mission

For a manned Mars mission, the probabilities of diseases and injuries are substantially higher than for a human Lunar base mission, especially during the Earth-Mars Earth transfers (Table 3.6). The following space-related disorders should be noted for this scenario:

- The radiation exposure likely to be experienced during a Mars mission is not fully documented. Permanent dose rate monitoring and an available radiation shelter are probably essential, both on board the transfer vehicle and in the Mars base (see Section 4.2).
- Bone demineralisation during the stay on Mars (0.39 x Earth's gravity) is unknown, but should be less than for an equivalent exposure to microgravity.
- During the transfers (and particularly for the two astronauts orbiting for 525 days around Mars with a total of 947 days in microgravity) the level of demineralisation could reach 50% at the pelvis, and it will certainly be more than the 15% threshold (considered as the level for significant increase of bone fracture risk). For that reason a temporary artificial gravity system (centrifuge on board the transfer vehicle) or a permanent artificial gravity system (permanent rotation of the habitable transfer vehicle) could be considered, but needs further investigations and studies to verify its effects on humans and its technical feasibility onboard the transfer vehicle.
- The space adaptation syndrome and Mars and Earth sickness (after Mars and Earth landing) need treatment for about three days after Earth launch, Mars landing and Mars launch – similar to that for the lunar programme. It should be noted that a temporary artificial gravity system (centrifuge on board the transfer vehicle) would probably increase the problem of the space adaptation syndrome by repeating the adaptation periods. Only a permanent artificial gravity system (permanent rotation of the habitable transfer vehicle) could bring some benefits. This might also reduce orthostatic intolerance (after Mars and Earth landing).
- Exercise capacity will probably decrease during the stay on Mars, but the magnitude of this decrease is unknown. Physical exercise devices should be provided within the Mars habitat. During the transfers between Earth and Mars, a decrease in exercise capacity would be serious, especially for the two astronauts with 947 days under microgravity conditions. To minimise the negative effects on muscle and work capacity, a physical training programme is mandatory. Physical exercise devices must be provided onboard the transfer and Mars orbiter vehicles. The type and duration of physical training must be defined and optimised. Again, a temporary or permanent artificial gravity system could be considered, but needs further investigation.

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Because an emergency return to Earth is impossible, even in the case of medical emergency situations, the medical equipment onboard the interplanetary parent ship and the Mars lander habitat stage must allow for all diagnosis and treatment in a much more autonomous way than required for the lunar base. In particular the surgical and medical diagnostic equipment, surgery equipment, surgery consumables and medication available "on site" must allow not only for the treatment and management of serious and minor injuries (fractures, crushing, extended burns, open wounds, sprains, strains, superficial injuries, local burns, contusions), but also for serious medical emergency situations (heart or cerebral stroke). In addition, all crew members should possess the necessary medical and surgical skills.

3.3.3 Crew health control needs for mission Scenario 3, the 500 day Mars mission

Like the 1000 day Mars mission, the short-term 500 day mission to Mars is associated with high probabilities of disease and injury, especially during the Earth-Mars-Earth transfers (Table 3.6). Therefore the requirements for the medical equipment onboard the interplanetary parent ship and the Mars lander habitat stage are similar to those for the long-term Mars mission. Provisions should be made to provide an emergency return from the surface of Mars to the interplanetary parent ship in the case of medical emergency situations on the surface of Mars.

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4 Limiting Factors for Human Health and Performance and Recommendations for Countermeasures

4.1 Introduction

Human spaceflight has undergone significant changes since its beginnings more than forty years ago. With the establishment of a space station in LEO, crews sent into orbit have become larger and more heterogeneous and the duration of spaceflights has increased. So far, the record is a stay of 438 days in LEO on the Mir space station. Our knowledge about human missions beyond LEO comes from the Apollo lunar programme, which was terminated in 1972 after a total of twelve astronauts had set foot on the surface of the Moon.

Future exploratory missions to the Moon and Mars, including the establishment of a permanently crewed base on the lunar surface, will extend the distances travelled, the intensity of the radiation, the gravity levels, the duration of the mission, and the levels of confinement and isolation to which the crews will be exposed. This will raise several health issues which may be limiting factors during these missions, in particular radiation health, gravity related effects and psychological issues. For missions to the Moon or to other planets, the safety measures employed so far in LEO have to be developed much further. Crew health and performance have to be ensured during transfer flights and planetary surface exploration, including EVAs, and upon return to Earth, within the constraints of safety objectives and mass reduction (see Chapter 3). Thus, prior to the design of an exploratory type mission (hardware and operations) as defined in Chapter 2, numerous issues in Life Sciences need to be addressed.

This chapter makes a critical assessment of the human aspects associated with long-duration exposures to interplanetary and planetary environments. For each of the three scenarios (see Chapter 2), we identify the impacts on human health, performance and well-being, of cosmic radiation including solar particle events, of microgravity (during space travel), of reduced gravity (on the Moon or Mars), of abrupt gravity changes (during launch and landing), of psychological issues and general health care. Countermeasures and the research required, using ground-based testbeds and/or the ISS, are defined.

4.2 Radiation exposure in space and on the Moon or Mars

4.2.1 Introduction

Since the very beginning of human spaceflight, ionising radiation has been recognised as a key factor of the space environment, potentially limiting the duration of human stays in space by its detrimental effects on crew health, performance, and – ultimately – life expectancy. Depending on the mission scenario, this environment consists of varying combinations of primary galactic, solar, and trapped radiation components, each of which has different radiobiological effects and each of which gives rise to complex secondary radiation upon passage through matter, including the human body (NCRP, 1989).

Long term human missions in space started with the Skylab crews, were extended by the Mir cosmonauts and will be extended further with the utilisation of the ISS.

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Common to these missions in LEO is the protection by the geomagnetic field which attenuates and essentially eliminates the threat posed by the stochastically occurring solar particle eruptions, and the – though initially limited – fast return capabilities in the case of unforeseen emergencies. So far, human missions outside the geomagnetic shield were limited to short visits to the lunar surface by the Apollo crew.

During colonisation of the Moon and missions to other planets, the protection provided so far in LEO has to be replaced by measures that are both available and effective within the spacecraft or habitat itself. Towards this goal, firstly quantitative estimates of the biologically effective radiation doses and the corresponding estimates of the radiobiological effects in man and their impact on the performance and life expectancy of the space crew have to be developed for each mission. Secondly, the limits of established knowledge and the implied uncertainties of the estimated effects, have to be identified and quantified. These limitations arise from uncertainties in empirical data describing the radiation fields and their temporal and spatial variation, in particular:

- the stochastic nature of solar particle events,
- assumptions and approximations made in models for transport and dose calculations (Wilson et al., 1989; Badhwar, 1997) and
- uncertainties of radiobiological models for early and late effects (and the corresponding sets of parameter values).

In particular, our limited knowledge of the radiobiological effectiveness of heavy ions of the GCR creates the greatest uncertainty in our assessment of the total radiation risk associated with such missions. Furthermore, during missions with prolonged phases in microgravity or low gravity we need to understand to what extent the risk estimates obtained by applying radiobiological models and parameters derived from terrestrial observation data can be applied to the altered physiological state to which the human body adapts in space (Todd et al., 1999). Finally, it has yet to be established to what extent countermeasures presently known to reduce health and performance detriments from ionising radiation are applicable and effective in space (Table 4.1).

4.2.2 Radiation exposure in interplanetary missions and on planets

Primary components of the cosmic radiation field which have to be covered are the fields of GCR and of solar particle radiation, both comprising mainly energetic protons as sparsely ionising, and heavy ions as densely ionising, particulate radiation and – in orbits around celestial bodies with magnetic fields – trapped radiation consisting of energetic protons. A component which only affects radiation exposures indirectly is the solar wind, which modulates the primary galactic heavy ions according to the rhythm of solar activity, with an average cycle time of around 11 years (Badhwar, 1997).

Although atomic numbers for all elements are found in the GCR, their intensities are negligible, for space radiation protection considerations, beyond iron. Figure 4.1 shows "extreme case" energy spectra of the primary galactic heavy ions, in free space at 1 AU distance from the Sun, for solar minimum and maximum. During times of maximum solar activity the low energy ions, below some 10 GeV/n, are suppressed by more than a factor of 10. Above ion energies of around 50 GeV/n the solar wind loses its shielding capacity. These extreme-case energy spectra serve as benchmarks for the variation of radiation exposures during the solar cycle. Apart from this variability through solar activity, these physical data concerning the primary GCR are among those with the smallest uncertainties in the context of space radiation protection.

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Table 4.1: Determinants of radiation hazards in human spaceflight

Primary Space Radiation Sources	**Radiation Transport through Shielding**	**Secondary Radiation Field**	**Internal radiation field parameters**	**Spaceflight Environment**	**Counter-measures**	**Biological Response**	**Radiation Health Effects in Man**
Galactic heavy ions **Solar particle radiation** • SPE • solar wind **Trapped radiation**	**Inter-planetary and planetary magnetic fields** **Mass shielding** • external masses • body self-shielding	**Electro-magnetic** **Electrons, muons** **Protons** **Neutrons** **Heavy ions (HZE-particles)**	**Charge spectra** **Energy spectra** **Linear energy transfer (LET-) spectra** **Organ dose** • physical • effective	**Microgravity** • direct/cellular interactions metabolism repair • indirect effects immune system hormonal/ metabolic/ fluid shifts **Closed environment** **Physical/ psychical stress**	**Avoidance** • mission planning/ operation • shielding (shelter) **Surveillance** • forecasting • dosimetry physical biological **Prophylaxis** • drugs, • crew selection, • induced radiation resistance (adaptive response) **Therapy** • drugs	**Dose/fluence response functions** **Biological weighting-(quality-) factors** **Single (HZE-) particle effects**	**Early effects** • early mortality haematopoietic death • early morbidity prodromal syndrome fatigue, anorexia nausea diarrhea, vomiting erythema • performance decrement **Late effects** • cancer incidence mortality • cataracts • hereditary

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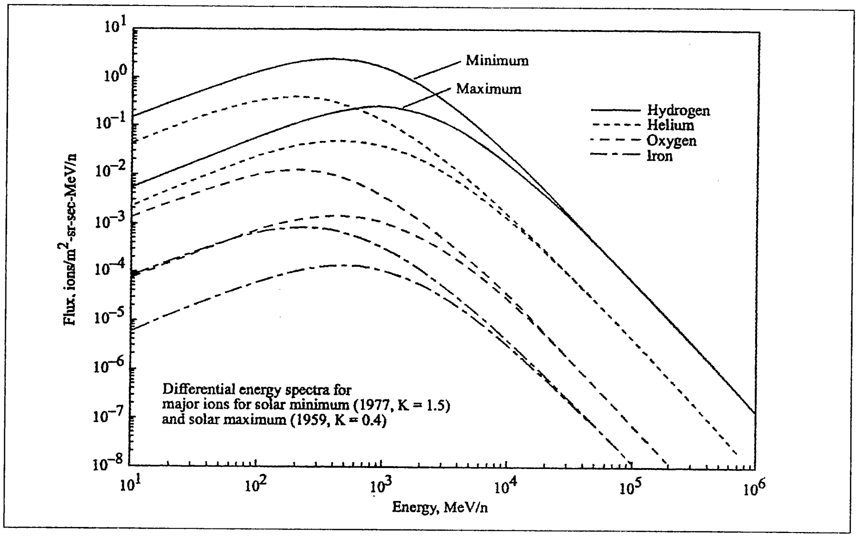

Figure 4.1: "Extreme-case" differential energy spectra of galactic cosmic heavy ions at 1 AU during minimum and maximum solar activity (from Badhwar, 1997).

Almost the opposite applies for the second, and in interplanetary space potentially dominating, component of the space radiation environment, the particulate radiation ejected during solar eruptions and further accelerated by coronal mass ejections (CME). The dominating constituents of these solar particle events (SPEs) are protons with energies reaching up to about 1 GeV, although occasionally lighter ions and higher energies are also found in these 'beams'. Figure 4.2 highlights the energy spectra of the "worst case" SPEs so far recorded. Presently only stochastic modelling approaches are available to manage and mitigate the health risk associated with individual events of

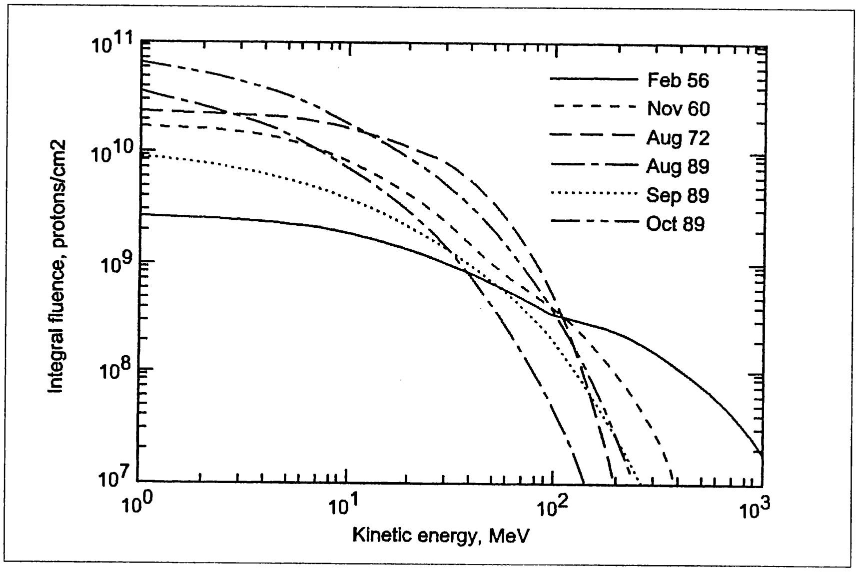

Figure 4.2: Integral energy distribution of protons observed in historical "worst-case" SPEs (from Nealy et al., 1997).

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this kind in space which have the potential for fatal consequences if they hit space crew outside sufficient shielding. In contrast to the gradual improvement in forecasting the imminent outbreak of individual events, the prediction of the radiobiological severity of an individual impending event, i.e. of its charge and energy distribution, of particle fluxes and their temporal profile is essentially beyond our present capabilities.

So far, for radiation protection shielding design studies, the energy spectrum of the August 1972 SPE (Figure 4.2) has conventionally been taken as reference event and most exposure and health effect estimates were derived from this spectrum. However, for future shielding and exposure studies, the SPE on September 29, 1989 has been suggested as its successor for this objective. The relatively high content of heavy ions and the short time, about two hours, to reach its maximum flux makes this particularly suitable as a worst case SPE candidate. In addition, the charge and energy spectral intensities of this SPE are multiplied by a factor of 10 to mimic the February 23, 1956 SPE, which produced the most intense ground level event so far covered by measurements, i.e. secondary neutron fluxes at sea level (Wilson et al., 2000).

Because the three mission scenarios do not encounter trapped radiation, apart from the exposure incurred during the short crossings of the terrestrial radiation belts, this contribution may be neglected compared to the remaining radiation levels.

In order to produce effects on health, the cosmic radiation components have to penetrate not only construction materials surrounding space crew, but also layers of less sensitive biological tissues, before they reach cells with significant sensitivity to ionising radiation. One of the more important tasks which still remains to be solved, concerning the transformation of the primary radiation components upon passage through shielding matter, is the proper treatment of secondary neutrons generated in the numerous kinds of spallation, fragmentation, evaporation, knock-on etc. reactions. Due to their high biological effectiveness/quality factor, their neglect may result in serious underestimates of radiation health effects. Particularly when heavy shields are involved, their relative contribution to the biologically weighted radiation exposure is bound to increase. But not only surrounding shield material serves as a source for these neutrons, even the surfaces of celestial bodies will act as such a source if accessible to the primary ions. Figure 4.3 gives examples of the energy fluxes of neutrons generated by GCR or an SPE in the atmosphere and at the surface of Mars. The corresponding doses and biologically weighted dose equivalents still need to be incorporated in the production codes of radiation transport models. Until this has been done, in the near future, their contribution will be missing from the exposure estimates for the reference mission scenarios.

For a quantitative assessment of the radiation exposures in space, a knowledge of the distribution of the surrounding shield matter as a function of shield thickness is essential. Fictitious step functions representing a homogeneous shield of an average thickness are useful at most for design studies in which the efficacy of different materials and compounds is compared. A typical – more or less realistic – distribution function for a prospective Mars vehicle is shown in Figure 4.4. Such a heavy shield with a median shield distribution of about 50 g cm^{-2} H_2O would be necessary if the current radiation protection limits for LEO missions (NCRP, 1989) were to be adhered to for worst-case radiation levels during a human mission to Mars. The choice of water instead of the conventional aluminium reflects the superior behaviour of hydrogen-rich materials in terms of charged particle – and also neutron – energy degradation and low secondary particle production. The lower median of about 42 g cm^{-2} H_2O during the return flight reflects the option to integrate consumables in addition to construction materials into the shield design.

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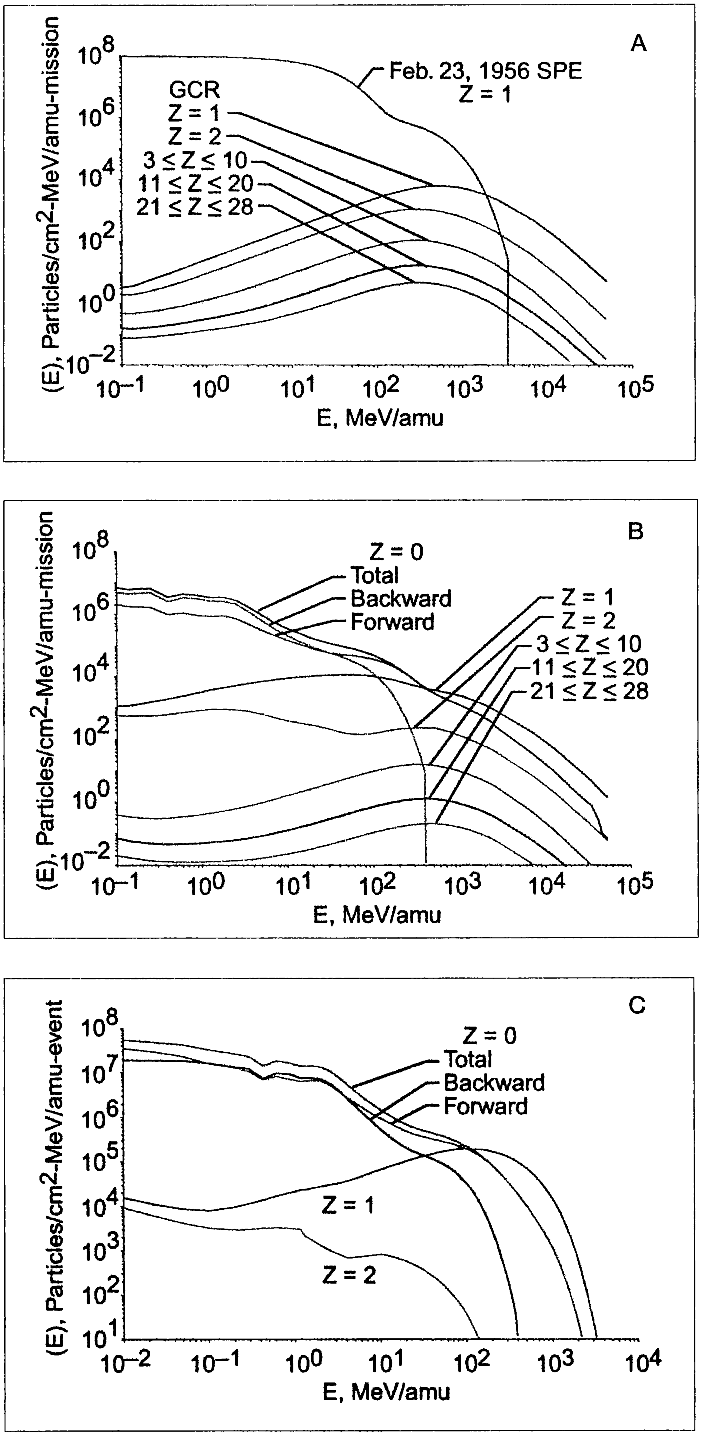

Figure 4.3: Mission integrated differential energy spectra at the surface of Mars of galactic heavy ions and one SPE (A), of secondary neutrons (Z = 0) generated by primary galactic heavy ions (B) or by primary SPE protons (C) (from Wilson et al., 2000).

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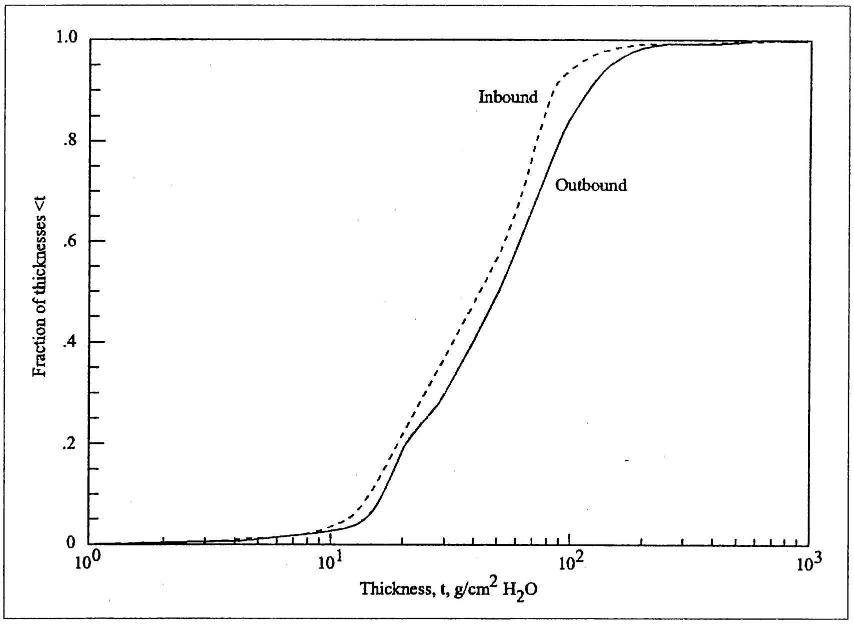

Figure 4.4: Shield thickness for a Mars transfer vehicle required to meet the radiation protection limits for LEO missions (from Nealy et al., 1997).

As for the vehicle wall, the thickness distribution around organs of interest must be known for a reliable determination of the exposure for these organs. The dose received by the blood forming organs (BFO) has conventionally been used as an approximation for the interior organs and for the whole body exposure. This is further justified by the fact, that fatal neoplasms of the BFO give rise to the most frequent radiogenic cancer, i.e., leukemia, which in addition has the smallest latency times of radiogenic cancers in adults.

Models for the components of the primary external fields of cosmic radiation give the charge and energy spectral intensities and the temporal and spatial variations of the respective components. Analytic and, even more so, Monte Carlo radiation transport codes preserve this type of information throughout the computational procedures. Hence, in principle, the most detailed information concerning the exposure of an organ or a cell is available to assess the biological consequences of this exposure. However, biological or medical response functions do not (yet) exist in terms of spectral particle fluences. Response functions for human health effects in terms of absorbed dose for exposures to sparsely ionising radiation do exist, but even these have substantial uncertainties. Hence the detailed information which in principle could be provided by the radiation transport codes has to be converted into substitute, secondary 'compound' quantities such as absorbed dose or equivalent dose where the biologically different effectiveness of the various components is to be expressed in terms of auxiliary quantities such as linear energy transfer (LET) according to Equation 4.1.

$$H = \int Q(L) * D(L)\, dL = c * \int Q(L) * (-L * \partial\Phi(L)/\partial L)\, dL \qquad (4.1)$$

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with:

H = the biologically weighted equivalent dose in Sv (Sievert),
Q(L) = the "quality-" or "radiation weighting-" factor as a function of the linear energy transfer, L,
D(L) = the density distribution of absorbed dose in LET,
Φ(L) = the integral distribution of particle fluence in LET, and
c = a unit conversion factor.

In this way, energy deposited in cells or organs by the very diverse types of secondary particles, such as photons, π- and μ- mesons, electrons, protons, neutrons and all conceivable fragments of either target or projectile nuclei, can be accounted for and weighted by the formally 'correct' biological weights (a function of their LET) assigned to these particles. However, the applicability of this approach to the components of space radiation, in particular to the densely ionising galactic heavy ions is one of the major uncertainties with which estimates of risks from these ions are fraught. Particularly for very densely ionising ions with large LET values, the experimental data become progressively dubious, if only for the formal reason that absorbed dose itself ceases to be a meaningful measure of exposure. Consequently, any assessment of space radiation hazards which follows the 'official' approach in calculating equivalent dose is already faced with the basic uncertainty whether the biologically weighted physical measure "equivalent dose" used for quantifying the radiation exposure is appropriate for a large and important fraction of the space radiation field.

However, until alternative measures such as, for example, fluence in conjunction with cross sections become established, the exposure to ionising radiation is to be quantified in terms of absorbed dose, modified by the radiation quality or weighting factor. During prolonged interplanetary missions, this dose has to be determined by integrating the corresponding dose rates of chronic exposures to the slowly varying galactic (and eventual trapped) radiation (Figure 4.5). In the case of exposures to solar particle events, the doses accumulated during these comparatively short exposures have to be added to the integrated chronic radiation dose.

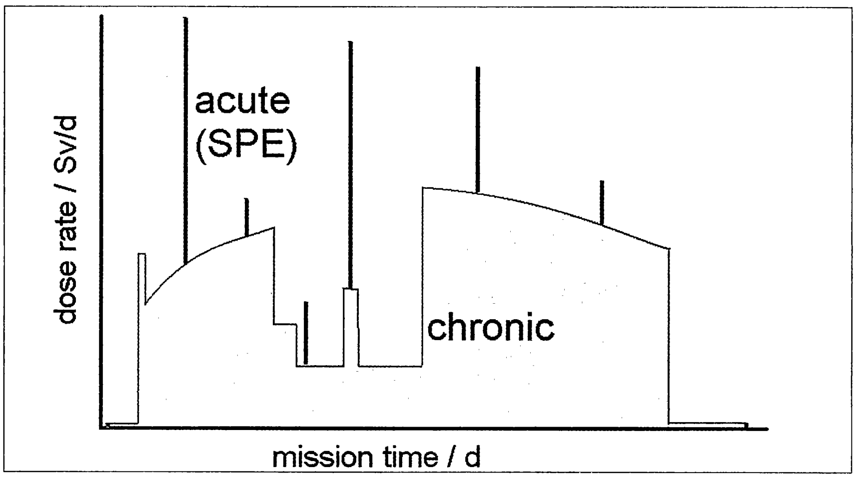

Figure 4.5: Fictitious but qualitatively representative example for varying dose rates during different phases of an exploratory mission with stochastic, 'instantaneous' dose increments from SPEs.

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The required equivalent dose rates from chronic exposure to galactic cosmic rays, for the different stages of the three mission scenarios, are summarised in Table 4.2 for different 'average' shieldings. The overriding importance of the timing of the mission within the solar cycle is immediately evident. Shifting a mission from a period of minimum to maximum solar activity reduces the dose rates in free space by factors of about 2.4 to 2.6, this gain being lower at higher shielding. On the other hand, increasing shield masses by a factor of 20 reduces dose rates by less than a factor of 1.4. The effectiveness per mass of added shielding material decreases by more than a factor of 2 from light to heavy shields. The advantage achieved by choosing hydrogen-rich shielding material is significant only at heavier shield masses and ranges between about 10% at 5 g cm^{-2} and 30% at 20 g cm^{-2}. On planetary or lunar surfaces, the dose rates for interplanetary space are roughly divided by two, due to the halving of the accessible solid angle if contributions from secondary neutrons are neglected. Further, substantial, attenuation is provided by the roughly 16 gcm^{-2} thick CO_2 atmosphere of Mars. In these calculations, the contribution from secondary 'albedo' neutrons on Mars, generated by galactic and solar radiation (Figure 4.3), are not yet included, so that the dose rates and doses given there are underestimates. It has to be emphasised that the actual, or at least realistic, thickness distributions for external and body self-shielding have to be used if more than qualitative comparisons are intended. Total mission doses or equivalent doses are then given by the temporal integral of dose equivalent rates over all phases of the mission (Table 4.2). Whereas for lunar missions the total radiation exposure is dominated by radiation received on the lunar surface, for the missions to Mars the exposure in free space dominates the total mission doses. Hence the Mars mission doses are rather similar for both scenarios, despite the difference of more than a factor of two in their duration.

A worst-case estimate for the acute, stochastic dose contribution from SPEs is given in Table 4.3. It shows the total equivalent event dose received from a single SPE, i.e. the SPE on February 23 1956, which has been approximated by multiplying the fluxes of the September 29 1989 SPE by ten. Although heavier ions are also present in varying amounts in SPEs, the bulk of the dose is deposited by protons and alpha particles only, the former dominating for all but the weakest shields.

For comparison with the exposures in Table 4.2, the age- and gender-dependent whole body career limits, for radiation exposures deemed to be acceptable in LEO/ISS operations, are given in Table 4.4. They have been developed with the aim of keeping the radiation-induced lifetime excess late cancer mortality below 3% and are subject to the additional constraint that any exposure must be kept *As Low As Reasonably Achievable* (ALARA principle). During mission Scenario 1, the lunar base mission, the exposure to GCR during one mission (Table 4.2) is fully compatible with the exposure limits for male and female crew at all ages, even with respect to the recently revised and more stringent thresholds. With moderate precautions several such missions would be feasible, even for female crew, within these constraints. Nominally, exposures during most of the more heavily shielded missions to Mars would also be compliant with these limits for females above 45 and males above 35 years of age (even if lighter shields were used). On the other hand the accumulation within less than three instead of ten years would tend to increase the resulting cancer mortality beyond its design value of 3%. Nevertheless, the possibility cannot be excluded that space crew might suffer larger radiogenic health detriment from these exposures, since the limits were derived from experience with terrestrial radiation sources, under exposure

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Table 4.2: BFO mission equivalent doses in mSv from GCR for the three reference scenarios

Spacecraft shield thickness	Solar activity	Shield material	BFO-dose equivalent rate in space	BFO-dose equivalent rate on the Moon	BFO-dose equivalent rate on Mars	BFO-Mission equivalent doses/mSv								
						Moon 190 d			***Mars 450 d***			***Mars 947 d***		
g cm^{-2}			mSv a^{-1}	mSv a^{-1}	mSv a^{-1}	10 d	180 d	190 d	420 d	30 d	450 d	422 d	525 d	947 d
		Alu	711.7	355.9	119	19.5	175	**195**	818.4	9.8	**828**	822.3	171	**993**
1	1977 min	PE	694.7	347.4		19.0	171	**190**	798.8		**809**	802.6		**974**
(pressure		Alu	271.7	135.9	61	7.4	67.0	**74.4**	312.4	5.0	**317**	313.9	87.7	**402**
vessel)	1970 max	PE	265.2	132.6		7.2	65.3	**72.6**	305.0		**310**	306.4		**394**
		Alu	646.9	323.5	119	17.7	159.4	**177**	743.9	9.8	**754**	747.4	171	**918**
5	1977 min	PE	584.3	292.2		16.0	144	**160**	671.9		**682**	675.1		**846**
(equipment		Alu	255.6	127.8	61	7.0	63.0	**70.0**	293.9	5.0	**299**	295.3	87.7	**383**
room)	1970 max	PE	229.2	114.6		6.3	56.6	**62.8**	263.6		**269**	264.8		**353**
		Alu	589.0	294.5	119	16.1	145.1	**161**	677.3	9.8	**687**	680.5	171	**852**
10	1977 min	PE	499.0	249.5		13.7	123.0	**137**	573.8		**584**	576.5		**748**
(shelter)		Alu	239.5	119.8	61	6.6	59.0	**65.6**	275.4	5.0	**280**	276.7	87.7	**364**
	1970 max	PE	198.7	99.4		5.4	49.0	**54.4**	228.4		**233**	229.6		**317**
		Alu	517.6	258.8	119	14.2	127.5	**142**	595.2	9.8	**605**	598.0	171	**769**
20	1977 min	PE	414.0	207.0		11.3	102.0	**113**	476.1		**486**	478.3		**649**
		Alu	217.7	108.9	61	6.0	53.7	**59.6**	250.3	5.0	**255**	251.5	87.7	**339**
	1970 max	PE	166.3	83.2		4.6	41.0	**45.5**	191.2		**196**	192.1		**280**

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Table 4.3: Worst case SPE radiation exposures in Sv during different mission phases for critical tissues under different mass shielding – given in parentheses in equivalent g cm^{-2} Aluminium;

Mission Phase	Contributing charges	Space suit (0.3)			Pressure vessel (1)			Equipment room (5)			Radiation shelter (10)		
		Skin	Lens	BFO	Skin	Lens	BFO	Skin	Lens	BFO	Skin	Lens	BFO
Free Space	Z=1	173.80	66.80	3.78	55.40	31.80	3.14	5.77	5.01	1.68	2.26	2.13	1.06
	Z=2	114.90	13.30	0.40	8.20	3.30	0.35	0.66	0.49	0.24	0.35	0.29	0.19
	3≤Z≤10	5.30	0.90	0.01	0.50	0.20	0.01	0.02	0.02	<0.01	<0.01	<0.01	<0.01
	11≤Z≤20	0.90	0.20	0.01	0.20	0.10	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
	21≤Z≤28	0.20	0.10	0.01	0.10	0.10	0.01	0.02	0.01	<0.01	<0.01	<0.01	<0.01
	Total	**295.10**	**81.30**	**4.21**	**64.40**	**35.50**	**3.52**	**6.48**	**5.54**	**1.93**	**2.62**	**2.43**	**1.26**
Lunar Surface	Z=1	86.90	33.40	1.89	27.70	15.90	1.57	2.89	2.51	0.84	1.13	1.07	0.53
	Z=2	57.45	6.65	0.20	4.10	1.65	0.18	0.33	0.25	0.12	0.18	0.15	0.10
	3≤Z≤10	2.65	0.45	<0.01	0.25	0.10	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
	11≤Z≤20	0.45	0.10	<0.01	0.10	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	21≤Z≤28	0.10	0.05	<0.01	0.05	0.05	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Total	**147.55**	**40.65**	**2.11**	**32.20**	**17.75**	**1.76**	**3.24**	**2.77**	**0.97**	**1.31**	**1.22**	**0.63**
Martian Surface	**Total**	**0.45**	**0.44**	**0.32**	**0.44**	**0.42**	**0.31**	**0.38**	**0.37**	**0.28**	**0.33**	**0.32**	**0.25**

Lens = ocular lens, BFO = blood forming organs

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Table 4.4: Age- and gender-dependent whole body dose equivalent limits in Sv recommended by NCRP (NASA) for LEO missions (from NCRP, 1989 and NCRP, 2000)*

Age/ at exposure	**25**		**35**		**45**		**55**	
	NCRP 2000	NCRP 1989	**NCRP 2000**	NCRP 1989	**NCRP 2000**	NCRP 1989	**NCRP 2000**	NCRP 1989
Gender								
Female	**0.4**	1.0	**0.6**	1.75	**0.9**	2.50	**1.7**	3.0
Male	**0.7**	1.5	**1.0**	2.50	**1.5**	3.25	**3.0**	4.0

** ten year career limits for a lifetime excess risk of fatal cancer of three percent*

Table 4.5: Organ specific exposure limits for the prevention of early/deterministic radiation sequelae of acute irradiation during different exposure intervals*

Exposure period	**Blood Forming Organs (BFO)**	**Lens of eye**	**Skin**
Career	–	4.0	6.0
1 year	0.50	2.0	3.0
30 days	0.25	1.0	1.5

** Recommended organ dose/organ dose-equivalent limits for deterministic effects (all ages); NCRP 2000: in Gy-eq/NCRP 1989: in Sv;*

conditions which may not correspond to the radiation components and conditions prevailing in space. If ensuing worst-case uncertaintries (a factor of 5 to possibly 15 lower) were to be accounted for, the limits would certainly be exceeded. Only exposures under the most heavily shielded missions, during maximum solar activity, would possibly be compliant with limits reflecting such worst case assumptions.

During missions at maximum solar activity, on the other hand, the probability of encountering a large SPE would significantly increase. The corresponding doses deposited by a 'worst case' reference event in deep space, as shown in Table 4.3, could possibly induce acute radiation injuries even behind 5 g cm^{-2} Al and, even in the so called shelter with 10 g cm^{-2} Al, the dose from one such event would surpass the total mission dose from GCR behind only 1 g cm^{-2} Al during mission Scenario 2. If such an SPE event would be encountered with only 1 g cm^{-2} Al or even less shielding, e.g. in a spacesuit during extra-vehicular or extra-habitat activities, severe, even incapacitating, acute radiation injuries could ensue, with a non negligible probability of a fatal outcome, unless adequate medical support could be supplied. The corresponding exposure limits, designed to prevent deterministic/early radiation sequelae from acute exposures, are given in Table 4.5. Since the bulk of the dose from an individual SPE is usually deposited

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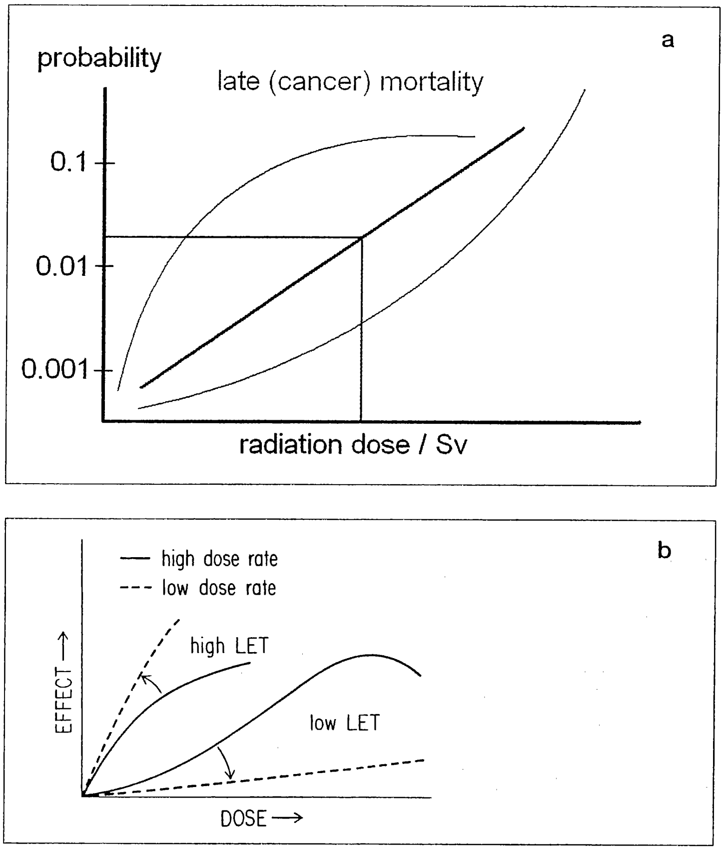

Figure 4.6: Dose response functions used for the prediction of late radiation effects and their dependence on ionisation density and dose rate.

in less than one day and even irradiation from multiple events rarely lasts longer than a few days, the values given in Table 4.5 for a 30 day exposure period would signify the appropriate thres-hold values. The limits for the blood forming organs (BFO) would be reached by such a worst-case event, even in the most protected environment on the surface of Mars, behind a radiation shelter of 10 g cm^{-2} shielding (Table 4.3). In the less protected surroundings on the lunar surface, and in free space, even the higher limits for the other organs would be approached and mostly exceeded within such a shelter.

4.2.3 Radiation effects in humans

Radiobiological effects in humans can be classified as early effects from acute radiation exposures, such as SPEs, and delayed or late effects from acute and chronic radiation, such as the GCR. The former are also called deterministic effects and have a probability as well as a severity of radiation sequelae that is a function of the dose. For the latter, so-called stochastic, effects only the probability of occurrence is a function of radiation dose. Late effects, such as enhanced morbidity or mortality from malignant cancers occurring up to twenty and more years after exposure, can be estimated from the accumulated radiation doses for each of the defined mission scenarios. Hence, late effects will not ensue until years, sometimes decades after completion of the mission. In addition, protraction of exposure reduces the likelihood that a given dose of – sparsely ionising – radiation will induce a given effect.

A straight line through the origin is presently adopted, for radiation protection purposes, as the response function linking the dose of an exposure to the probability of producing a fatal cancer and thereby reducing life expectancy. This expresses the "linear, no threshold (NLT)" hypothesis of applied radiation protection (Figure 4.6a). The presently recommended value for the slope of that line is $4x10^{-2}$/Sv for the induction of excess cancer mortality by chronic irradiation. Multiplication of the cumulated mission doses of the three mission scenarios by this factor, as given in Tables 4.2 and 4.3, would then give the probability of death, ten to twenty (or more) years after exposure, from an excess cancer due to a radiation dose of galactic heavy ions accumulated during such a mission. It should, however, be noted that a linear dose response function is hardly ever encountered in radiation biology experiments,

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especially with animal or mammalian cell models. Instead, more complex functions are usually observed (Figure 4.6b).

For other late effects, such as late cataracts of the ocular lens which can be cured effectively, the original consideration of this condition as a health risk no longer seems to be warranted, least of all in the context of pioneering space exploration. Genetic, hereditary late effects from exposure to ionising radiation have never been observed in human populations and therefore they will not be considered as health risks in this context, in particular since crew members of the first missions will probably have passed the reproductive phase.

Early effects from ionising radiation 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 haematopoietic, the pulmonary and the gastrointestinal systems. Frequencies and intensities of symptoms are determined as functions of the received acute radiation doses, which in general have thresholds, below which clinical symptoms cannot be observed. Estimates of the impact of these symptoms on the performance of military crew as an additional factor potentially interfering with mission success have been derived within the "Intermediate Dose Program" (IDP) of the US Defense Nuclear Agency. IDP has established quantitative relations between performance degradation as a function of time after exposure and dose for various military crew members. Such estimates might be useful for operational decisions in the case that unforeseen high exposures, due to a so far unobserved 'giant' SPE, would occur.

Normally no space mission design will allow foreseeable worst case exposures to surpass the thresholds where symptoms for early, deterministic, radiation health effects are to be expected. In the three reference scenarios acute doses can only be expected to be deposited by SPEs. Although total mission doses from galactic heavy ions may surpass the doses from single, normal, SPEs, the repair/recovery capacity of the human body can undo the damage incurred at these chronic dose rates, as long as these remain low enough to not impair the recovery/repair capacity itself, which again under normal circumstances can be excluded by design. In this case, the profile of the September 1989 SPE would be a suitable worst case example, due to its rather fast rise time and also the low total duration.

4.2.4 Influence of spaceflight parameters on radiation effects in humans

Earlier radiation protection recommendations of the International Commission on Radiological Protection (ICRP) explicitly accounted for the possibility of environmental interactions with the expression of radiation injury by explicitly introducing a dose modifying factor, N, in Equation 4.1, whose value for terrestrial environments, however, has now been set at unity by the current recommendations, so that in effect it has been dropped altogether. In interplanetary missions, the most important factor that could modify radiation response functions is weightlessness (or reduced gravity). The ecologically closed/confined environment of the vehicles and planetary habitats may give rise to further interactions with the expression of radiation effects. The physicochemical and microbiological environments will almost certainly differ significantly from those to which the human body is optimally adapted. Finally this environment will exert significant psychological pressure – at least during the missions to Mars.

The question whether physiological changes induced by microgravity might interfere – either synergetically or antagonistically – with the expression of

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radiobiological effects, was addressed rather early. Several human organs, tissues and pathways are known to be affected by microgravity or by general, including psychological, stress (see Sections 4.3 and 4.4) and these may participate in the expression of radiation effects. Following quite inconclusive experiments on interactions between microgravity and radiation, on *Biosatellite II*, the US National Academy of Sciences (NAS) concluded that further studies addressing this problem were not warranted. Early Soviet experiments with rats irradiated during short term LEO missions with low LET artificial radiation sources resulted in a dose-modifying interaction with microgravity by at most a factor of 1.2. European investigations during the Spacelab era, using the *BIOSTACK* concept, suggested that the effects of single galactic heavy ions on insect embryogenesis are aggravated in microgravity. On the other hand it has been established that in cellular systems, including human cells, repair mechanisms that restore proliferative capacity after irradiation with low LET radiation perform undisturbed in microgravity (Horneck et al., 1997).

A specific indirect influence of the spaceflight environment on radiation-induced cancer mortality might be brought about by the reduced competence of the immune system, caused by prolonged exposure to microgravity. At least for those tumours whose promotion and final expression can be controlled or suppressed by the body's immune response, the possibility is evident that its reduced capacity may enhance the expression of tumours. Impaired immune competence, which might result from acute exposure to higher levels of radiation, is also a risk in the closed environments in which crews will be locked for significant periods.

In summary, it remains unclear whether the response in humans to ionising space radiation would be aggravated or attenuated by microgravity. Particularly during long term missions, potential interactions might modify the course of physical, chemical, and biological events which link the primary molecular radiation damage with the final clinical symptoms. The material presented here clearly substantiates the hypothesis that this might be the case. The known shift in microgravity towards the pro-oxidant state, and the reduced immune competence, favour the speculation that this might result in an aggravation of the radiation response. However, the amount by which the risks might be quantitatively affected remains open to speculation and is bounded only by epidemiological data that so far exist, or could be established, on space crew with substantial long term exposures.

4.2.5 Radiation risk assessment and associated uncertainties

Present guidelines for radiation protection in LEO missions were derived starting from a postulated 'acceptable' risk for late cancer mortality, which had been justified by comparison with mortality rates from 'normal' terrestrial occupations (NCRP, 1989). Radiation exposures from previous spaceflight activities within the geomagnetic shield, in LEO and inside the ISS, are sufficiently low that no special actions were necessary to keep within these NCRP limits. However, as Tables 4.2 and 4.3 indicate, the doses expected during the three exploratory mission scenarios, especially during the missions to Mars, are likely to exceed these limits unless mass shields are installed, which could strain the capacities of the propulsion systems. In addition to late cancer mortality, and this is a decisive difference, the possibility that crew members might suffer from early radiation sickness induced by significant SPE irradiation – e.g. during extra-vehicular or extra-habitat activities – does imply a non-negligible risk for early mortality – either directly, or indirectly via performance reduction resulting from the associated symptoms. Given the probably substantial total costs of, for example, a manned mission to Mars, a further decisive distinction is that investment in

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genuine radiation protection will take resources from other measures which might improve overall mission safety. Among the technical causes of early mortality, in addition to direct radiation effects on vital electronic systems, space radiation can indirectly increase death rates during the mission by, for example, straining the propulsion systems with the substantially larger masses required for sufficient mass shielding or by exhausting the mass budget otherwise available for additional medical or life support equipment. Reducing the radiation risks might, therefore, indirectly increase the early mortality risk during the mission.

In short, for exploratory type missions, the premise for choosing late cancer mortality as the decisive criterion for space activities in LEO (NCRP, 1989) does not hold. Instead, a criterion is needed which accounts for mortality risks from all mission-related sources and also assigns greater weight to sources of early mortality during the mission than to late mortality fifteen to thirty years after the mission. A useful quantitative criterion satisfying these requirements is the Healthy Lifespan Lost (HLL) from mission related causes, defined as

$$HLL = \int_0^{L_A} L^* \, m\,(L;A) \; {}^*dL \qquad (4.2)$$

Here L would measure the total remaining lifespan after the mission, beginning at 0, the last year of the lifespan up to L_A, the normal lifespan expected at age A of the crew member at the start of the mission. The mortality rate m(L;A) would include the early risks during the mission and the risks for late excess mortality. Since late cancer mortality depends on age at exposure, A would be an additional parameter. Furthermore, given that the quality of life after diagnosis and therapy of a potentially lethal cancer may be considered as severely impaired, it is reasonable to include not only fatal cancers but the incidence of all cancers, i.e. morbidity as well (Figure 4.7).

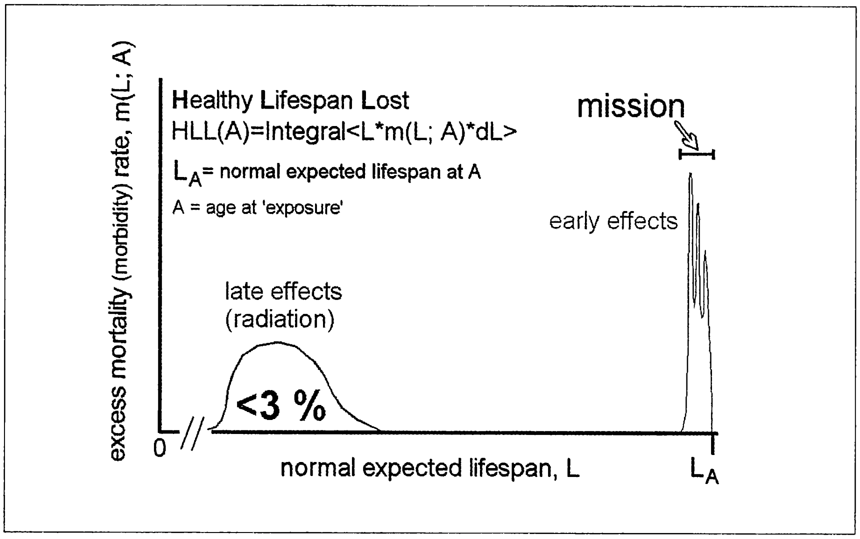

Figure 4.7: Determination of HLL, the Healthy Lifespan Lost due to early mortality during the mission from all causes and delayed mortality/morbidity due to late radiogenic cancer from radiation exposures during the mission.
(Note: as time and age A increase, normal expected lifespan, L, decreases). Three percent late radiogenic cancer mortality represents the present design criterion for LEO missions.

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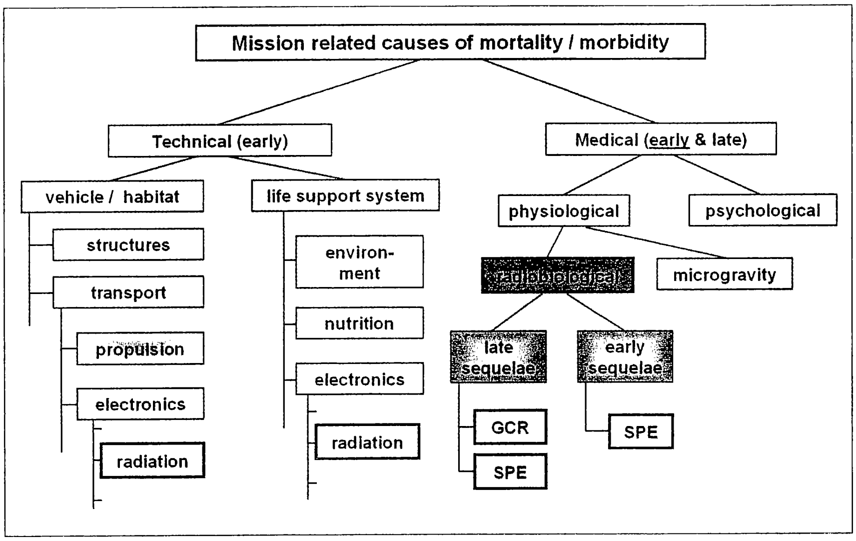

Figure 4.8: Major radiation-related components affecting the minimisation of Healthy Lifespan Lost as the primary design criterion which treats all mission related causes of early and late mortality in a unified manner.

Then, minimising the healthy lifespan lost, HLL, within the constraints imposed by the mission's objectives on the one hand and the resources allocated to its fulfilment on the other hand (Figure 4.8) would be the design goal for any measures designed to improve overall mission safety. This would lead to an integration of the radiation risk assessment into the total risk analysis of the mission. The implementation of this integrated approach then demands that a mission be quantitatively specified in every relevant detail.indicated in Figure 4.8.

The return gained from the substantial additional effort necessary to implement the HLL criterion is that this criterion:

(i) deals adequately with the dichotomy between early and late radiation sequelae,
(ii) unifies the assessment of technical and human radiation hazards, and
(iii) yields a single number whose minimisation
  (a) offers release from the 'curse' of worst case design (e.g. SPEs) and
  (b) reduces the uncertainties inherent in radiobiological risk assessment.

The physical and biological factors determining radiation risks for HLL include, among others, the absorbed dose, the radiation quality, the dose rate, the exposure conditions, age, sex, health, genetic disposition, and socio-economic/cultural factors (Figure 4.9).

The only purely physical factor determining radiation risk is the physical absorbed dose deposited in a given organ. The models describing the spectral fluxes of GCR particles in interplanetary space and their rather smooth and regular temporal variation with the solar cycle have steadily and significantly been improved during the last three decades. Less well known is the spatial variation of GCR fluxes with the distance from the Sun. Regarding SPE spectral fluxes, the database of spectral measurements again allows for rather robust estimates of total accumulated particle fluxes, at least for not too short time periods. However, the adoption of the empirical frequency distributions as a basis for probabilistic flux predictions presumes that the time period covered by satellite measurements is also representative for future solar cycles.

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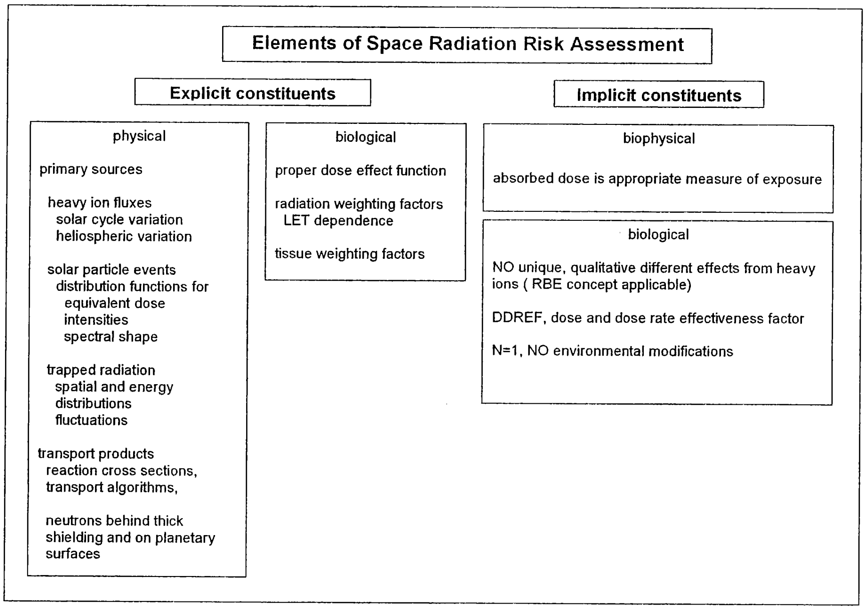

Figure 4.9: Overview of factors determining the risk associated with exposure to space radiation.

During the last three decades, the methods developed to calculate the transport of primary SPE or GCR particles through mass shields specified in terms of atomic composition and geometric arrangement have drastically improved. The necessary cross sections for the production of secondary particles through target nuclei spallation or projectile fragmentation have been improved by substantial algorithmic advances and by theoretical and semi-empirical modelling, combined with relevant measurements for nearly the complete energy range. Most recently, the contributions from secondary neutrons whose fluxes become important or even dominant for very thick mass shields in interplanetary space or – as albedo neutrons – on planetary surfaces, are being accounted for with significantly improved accuracy. As a consequence, for most shield configurations, predictions of organ doses can be made with sufficient or at least acceptable accuracy.

Much higher uncertainties in radiation risk assessment are associated with the biology-related factors. This uncertainty already starts with the question of what the shape (the analytical form) should be of the 'true' dose response function which adequately describes the single most important database, the epidemiological findings from the Japanese atomic bomb victims. Further uncertainties arise from the different radiation qualities and exposure conditions experienced by both groups, the group of space explorers and that of atomic bomb victims.

A significant open problem of risk assessment for space radiation protection is whether the functional dependence of radiation weighting factors on LET, as defined by the ICRP (1991), correctly models the biological effectiveness of the complex mixture of space radiation 'qualities'. The conceptual pair of particle fluence and effective cross section, instead of dose and radiation quality, might be the proper way to express the biological effectiveness. This conceptual framework

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is the preferred setting for planning experimental radiobiological research designed to reduce the uncertainties associated with 'radiation quality'. The preferred experimental technique is to study the effects of single charged particles on individual cells – as previously developed for the radiobiological BIOSTACK spaceflight (Bücker & Horneck, 1975) and associated accelerator experiments – and more recently in the so called microbeam experiments. Theoretical work to link the conventional absorbed dose and quality factor approach to the fluence and effective cross section concept might help to convert data from one realm to the other, thereby enlarging the empirical database for both approaches.

On the physical/dosimetric side a significant new piece of information relates to the SPE impact on the HLL. Instead of designing countermeasures for a putative worst-case event, probability distribution functions are required for the accumulated effective dose deposited by all SPEs occurring during the mission, as well as for the biologically effective dose deposited acutely in critical organs during a single SPE. Whereas the former would add to the equivalent doses responsible for late cancer mortality/morbidity, the latter could raise the early mortality due to either directly or indirectly increased probabilities of fatal events. Since mortality rates deduced from these single SPE doses would be conditional on the event that such values in fact did occur, the above HLL would have to be replaced by its expectation value <HLL> under these distribution functions. Such distribution functions depend on the mission duration, mass shielding, and solar activity phase as major relevant factors. For any given mission, one such distribution function for each dose – total mission dose and single event dose – would pertain. Since, during periods of minimal solar activity, SPEs yielding significant radiation doses are virtually absent, the primary factor determining these distribution functions is the phase of the solar cycle during which the mission takes place. In contrast, the conventional 'worst case' approach to SPE-related radiation hazards considers only the amount of mass shielding and the maximum dose value pertaining to the largest possible event, i.e., the upper limit of the range belonging to the corresponding distribution function.

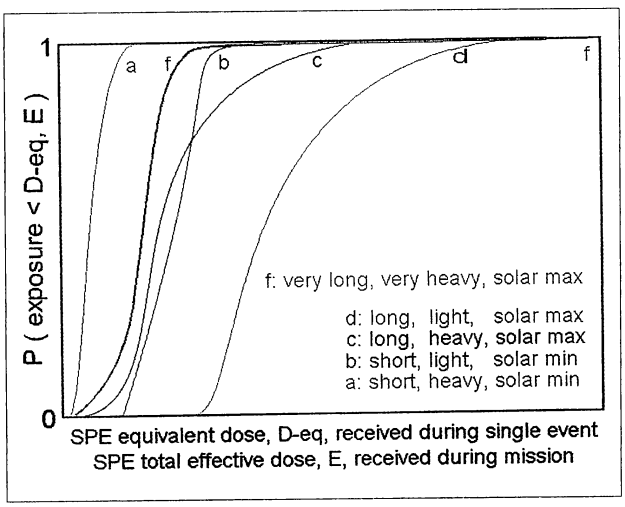

Figure 4.10: Fictional distribution functions of equivalent dose, as required for a probabilistic treatment of risk assessment for defined mission phases, in terms of duration, mass shielding and solar cycle position.

The empirical basis necessary for estimating these distribution functions increases steadily with the time for which charge and energy spectra have been measured with satellite borne radiation detectors, i.e. for about four solar cycles. The estimation of these distribution functions could draw on a large database of measured spectra of SPE particle fluxes and, apart form the upper tail, these estimates are likely to yield rather reliable probabilities (Figure 4.10). Even the empirical estimates for the upper limit of the doses potentially received in a single event, and hence for the empirical range of the distribution, steadily improve and accordingly the estimates of the upper tails of the distribution functions are expected to become more and more stable. The database itself is established mainly in terms of

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charge and energy spectra, and though in principle no new methods are required, it remains a substantial computational task to convert these data into distribution functions of biologically weighted organ doses received behind mass shields of a specified composition and spatial distribution.

On the biological side, estimation of the *direct* contribution of single SPE exposures to early mortality might be obtained by means of the dose effect relations as specified originally by NRC (1985) and its revision (NRC, 1993) and more recently in (NRPB, 1996), and would be a relatively straightforward task. The success of these predictive models in recent terrestrial findings (Scott et al., 1998) and, in particular, the definition of pertinent RBE (relative biological effectiveness) values by NRCP (2000) would render such assessments quite reliable. However, *indirect* contributions to early mortality due to fatal performance reduction, as secondary effects of symptoms of early radiation sickness, would probably require major new developments. Previously, such ionising-radiation-induced performance reductions had been estimated for military crews in nuclear battlefield scenarios (e.g. Anno et al., 1984; Inman et al., 1993). Although significant results for task-specific dose and time-dependent performance contours could be established by involved and sophisticated methods specifically developed and validated for this purpose, the working environment and the task spectra of space crew would most probably require a major redesign of these methods in order to yield relevant and reliable results. The methods developed for the integrated performance modelling as described during this study (see Chapter 6) appear to provide more advanced tools that are capable of performing this task. The efforts associated with this appear to be worthwhile, if only to establish that this indirect contribution to early mortality and hence HLL might be negligible.

Regarding the question of "mission criticality", radiation exposures that are high enough to have an impact on successful mission completion can only occur during SPEs that engender early radiation sequelae. Apart from this, mission success can be affected only indirectly by improper, overly conservative risk estimates that strain mission/habitat design with unnecessary protective countermeasures, consuming resources that could otherwise have improved mission safety.

4.2.6 Surveillance of radiation exposure

Monitoring the radiation exposure of the crew members as precisely and comprehensively as possible is mandatory, if only to keep a record of the physical exposure, which might be re-analysed once significantly new insights have been gained into the biophysical and biomedical mechanisms of radiation health effects from exposure to cosmic radiation. In addition and more importantly, a reliable dosimetric record is a prerequisite for adequate operational decision-making during a mission, in case the decisions would alter the expected exposure.

Physical devices to measure the exposure to cosmic radiation have been used in all missions, since the very beginning of manned spaceflight forty years ago, and any progress achieved for terrestrial applications was soon exploited for space radiation dosimetry, such as tissue equivalent ionisation chambers or thermoluminescence detector systems. For the given mission scenarios the most important device will be an onboard monitoring system capable of detecting, as soon as possible, any SPE that might affect the region surrounding the crew. In order to maximise warning times, such an onboard system will have to be integrated with other monitoring systems in interplanetary space and on other celestial bodies, including Earth. The physical detector systems necessary for such

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measurement tasks are available and the only remaining – but by no means trivial – task is their integration into such an overall system.

The adaptation to the space radiation field of genuine dosimetric devices which can determine the absorbed dose or equivalent dose rates is much more demanding and can usually only be achieved with substantial compromises. In particular, the biological interpretation of absorbed dose and equivalent doses has to rely on the validity of assumptions which may not hold true or at least still have to be verified. The only 'model free' active monitoring system would have to record the particle fluxes at the locations of interest, i.e. in the crew habitats, resolving them according to their charges and energies. The realisation of this requirement for the time-resolved monitoring of dose rates will again only be possible with significant compromises in the achievable spectral resolution. In contrast, accumulating passive detector systems, such as nuclear emulsions or other visual particle track detectors, in principle offer better spectral resolution at the expense of the missing temporal resolution. Hence, in line with the practice during all human missions so far, a physical radiation monitoring system will have to combine both types of detector, in order to yield a comprehensive and precise record of the radiation exposure during the mission.

Bioassay or biosensor systems useful for monitoring the habitat and the advanced life support systems (see also Chapter 5) are a necessary complement to purely physical detector systems, in as far as they yield intrinsically biologically weighted measures of the exposure to the whole complex radiation field. In particular those systems, whose signals quantify the molecular damage to the DNA or chromosomes, are especially relevant for surveying the mutagenic and carcinogenic impact of the radiation environment together with other potentially genotoxic constituents of the habitat, such as polyaromatic hydrocarbons and aromatic amines or hydrazine/azo-compounds, which have been demonstrated as off-gassing products in Shuttle and Mir air samples. Potential synergism with radiation of these known tumour initiators and promoters, increases the importance of biologically monitoring the combined effect of such factors.

As an intrinsic biomarker, the scoring of chromosome aberrations – i.e. of aberrant karyotypes in peripheral lymphocytes – has a longstanding history as a successful biological radiation monitor, in particular in cases of radiation accidents, where physical dosimetric data are often lacking. Its intrinsic biologically weighted response to different radiation qualities offers a, so far unique, possibility to monitor the exposure to the complex space radiation field in terms of a truly biologically weighted 'equivalent' dose – in spite of the possibility that the quality response function may be different from that for conventional early or late radiation effects. Individual variations among crew members regarding the sensitivity to this effect could also easily be detected. For this reason, scoring of chromosome aberrations should be considered as an additional, complementary 'detector system' for space radiation dosimetry. The substantial problems associated with the adaptation of the terrestrial processing and analysis techniques to the spaceflight environment have so far prevented the utilisation of this biomarker in space, although post-flight terrestrial analysis of lymphocytes from long term astronauts have verified the potential of this system as a biodosimetric tool.

In addition to chromosome aberrations in lymphocytes, monitoring of the other blood constituents is a standard requirement for the planning of therapeutic measures to be taken after radiation accidents where – again – immuno-suppression effects are mediated through reactive oxygen species. In fact, it is axiomatic that

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therapeutic actions should never be taken solely on the basis of physical dosimetric information. Instead, analyses of the haematological and immunological status of blood samples are mandatory for the planning of remedial actions after radiation accidents, since these data have a much stronger prognostic power than the physical dosimetric data. Hence, as a surveillance technique for anticipated exposure histories, as well as a prognostic tool in case of accidental exposures to SPE radiation, equipment and crew expertise for these analyses should be part of the risk management regime. Most likely this will pose only a minor – if any – additional demand on the general medical support that is anyway available on board. Nevertheless, the higher the probability that such accidental exposures may occur, the more necessary this capability becomes.

Given the oxidative stress induced by chronic radiation exposure – and perhaps the spaceflight environment – and the role of such reactive species in both tumour initiation and promotion, bioassays which are sensitive to by-products of radiation-induced oxidative events in blood or urine samples would constitute an important biological monitor, not only of radiation exposure but potentially also of the effectiveness of chemo-protective prophylactic countermeasures. Provided that recent terrestrial advances in these techniques could be adapted to spaceflight conditions, such bioassays for e.g. 8-hydroxydeoxyguanosine, malondialdehyde, or 4-hydroxy-2(E)-nonenal would constitute a most valuable addition to the surveillance component of the risk management system.

4.2.7 Countermeasures against space radiation hazards

Given that any exposure to ionising radiation – at least above some, as yet undefined, threshold – carries the potential for significantly reducing the life

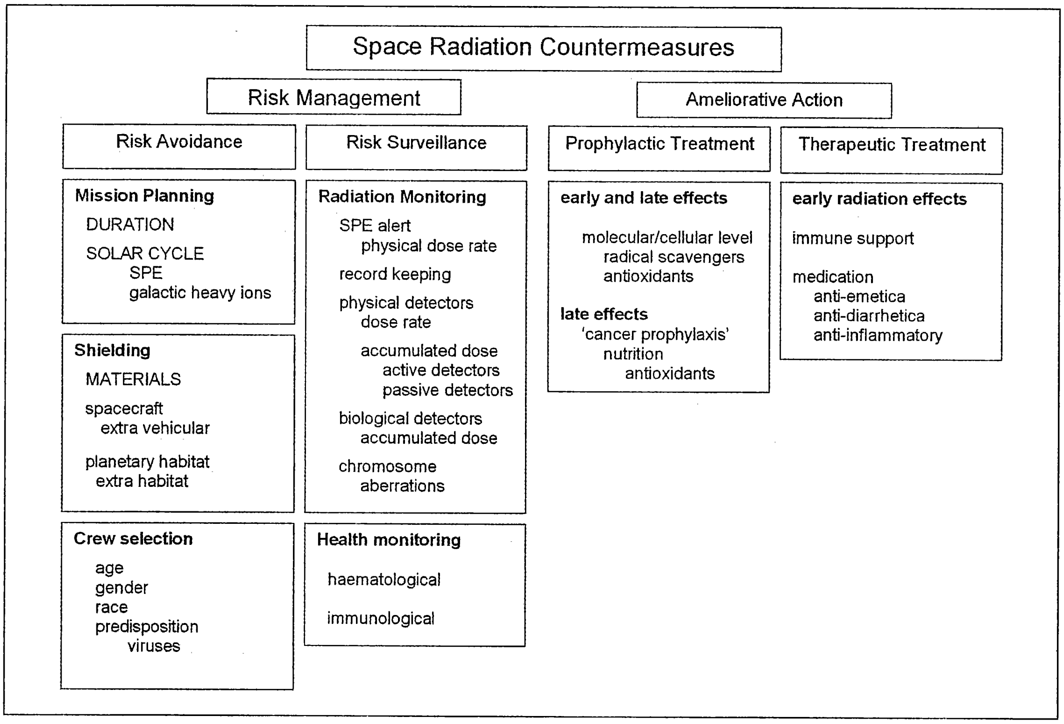

Figure 4.11: Overview of countermeasures against health effects from space radiation.

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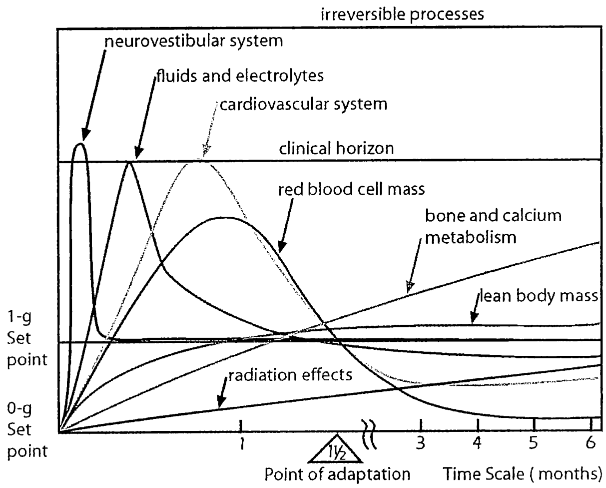

Figure 4.12: Temporal development of radiation effects and of microgravity adaptation processes of major physiological systems during long-term spaceflight.

expectancy of those exposed, the only true countermeasure against radiation is avoidance of exposure beyond that limit (Figure 4.11). Any measures conceived for reducing the consequences once that an exposure has taken place, therefore have to be considered as of secondary importance only.

Among the countermeasures available for reducing risks from radiation in space, three classes of avoidance strategy are discernible:

i careful planning of mission duration,timing and operations;
ii surrounding crew habitats with sufficient absorbent matter;
iii increasing the initial resistance of exposed personnel to the negative effects of exposure.

Since radiation risk is a monotonically increasing function of mission duration, the most effective avoidance countermeasure is, in fact, to restrict exposure times to the absolute minimum. This principle may make it worth considering, in the context of the Mars missions, the feasibility of drastically reducing mission duration by developing alternative propulsion systems. To the extent that other potentially limiting factors such as medical/physiological problems from long term exposure to microgravity or psychological problems from long term confinement and seclusion might even increase dramatically with mission duration (Figure 4.12), more powerful propulsion systems would probably be the countermeasure with the optimal cost-benefit ratio.

The attempt to manage risk by choosing – within the constraints imposed by celestial mechanics – the timing of a mission with respect to the cycle of solar activity has to be balanced against other things. Exposure to GCR – with its large, but still not well understood, radiobiological effectiveness – is minimal during phases of maximum solar activity, which clearly would favour such a choice. On the other hand, high solar activity implies increased probabilities of larger doses from solar particle events. In particular, the giant SPEs so far observed, always

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Table 4.6: Parameters relevant for radiation exposure assessment in exploratory type missions.

Mission parameters	**Radiation exposure**			
	Acute radiation from SPE Number of events mGy/event		chronic radiation µGy/day	
	Low LET	High LET	Low LET	High LET
Duration				
Solar Distance/AU				
Solar cycle time				
Mass Shielding Distribution				
Mission Phase				

occurred during, or shortly after, the maximum of solar activity. Any quantitative risk/exposure trade-off between these alternatives requires the detailed specification of the complete mission, for example in terms of the parameters listed in Table 4.6. Also, the specification of an average shielding material and thickness cannot replace the required detailed mass distribution function as shown, for example, in Figure 4.4. Only risks calculated in this detail can furnish a reliable basis for the choice of a 'minimum risk' mission with respect to its temporal position in the solar cycle.

Regarding the material composition of shielding against space radiation it has been established that, due to low build-up of secondary radiation products within the absorber, hydrogen would be the optimum choice, rather than the 'standard' shielding material, in particular for shielding against GCR. Hydrogen-rich solids like polyethylene or liquids like water represent good approximations of this optimal material. Integration of food or water resources into the design of shield distributions however is – in addition to structural and mechanical constraints – limited by the fact that these are likely to be consumables, which would reduce shield efficiency during the Earth-bound return phase. On planetary surfaces, mass shielding of stationary habitats, of any desired thickness, could in principle be furnished by surface materials, provided the necessary construction facilities were at hand. Whereas for the missions to Mars the added masses for the transport of such construction equipment – including the necessary fuel – may limit the exploitation of this possibility, this should not be a problem for the lunar scenarios. Nevertheless, the requirement that extra-habitat activity may only take place if a shelter with sufficient shielding against SPE irradiation can be accessed quickly enough, may constrain such missions on lunar surfaces more severely than on Mars, due to the shorter time available for SPE warnings.

As far as avoidance of risk by proper selection of crew members is concerned, the choice of older crew members will reduce the probability of the loss of healthily lived years after the mission and therefore should be exploited within the limitations imposed by the requirements for physical fitness. Although seldom considered explicitly in space radiation protection, age beyond the usual human reproductive phase will also avoid the risk of teratogenic consequences in offspring conceived after the mission.

Gender differences in susceptibility to cancer induction would favour male crew members, due to the added risk of females developing breast cancer. This may have to be balanced against a psychology-related requirement for mixed gender crews.

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Racial differences in the susceptibility to spontaneously develop cancers in different organs are well documented. Less well established is the extent to which sensitivity to radiation-induced carcinogenesis differs between races, despite circumstantial evidence that this might be so. The prospects for clarifying this further appear meagre, since only epidemiological investigations could furnish empirical data and it would be difficult to collect the very large number of samples needed for statistical significance.

Large differences between individuals in sensitivity to ionising radiation have also been observed for many years in radiation therapy. However, all the variations described so far relate to seriously increased sensitivity associated with other, genetically determined, diseases. The search for genetic 'markers' which may signify or even cause increased resistance of normal tissue towards radiation induced carcinogenesis has been spearheaded by the quest of therapists for optimised radiation therapy treatment plans for cancers. Although the relevance of the positive – mainly phenomenological – findings obtained so far for the extremely large exposures during radiation therapy is limited for the purposes of radiation protection, the current rapid advances in our knowledge of the human genome has stimulated several research teams to propose the exploitation of the related techniques now available for research activities to elucidate the genetic and molecular basis for these phenomenological observations. Such research is often proposed under the banner of 'research into the molecular/genetic basis of the "inter-individual variability" of biomedical phenomena' and the growing intensity of such research activities justifies the expectation that results may be found in time to be useful for the identification and subsequent selection of crew members with increased resistance to the induction of early as well as to late radiation sequelae. Identification in the individual genome of virally derived genetic material which may confer increased sensitivity would be a valuable supplementary result, if it prevents the selection of aspirant crew members with such latent risks.

Less spectacular than the previous approach, but with a well established empirical foundation, is the possibility that increased resistance against 'higher' doses of ionising radiation can be induced by pre-irradiation with lower conditioning doses. These findings are interpreted as an 'adaptive response' due to the stimulation of the ubiquitous cellular repair systems, which normally eliminate nearly all of the molecular lesions that result from the initial assault of ionising radiation on the cellular constituents. However, the findings accumulated over more than fifteen years have been obtained with non-human model systems and predominantly with sparsely ionising radiation. Further progress in elucidating the precise molecular mechanisms involved, possibly assisted by progress in the previously mentioned research activities, will probably clarify to what extent these processes may also be effective for protection against the vastly different radiation exposures in space.

If, in spite of all careful avoidance practices, damaging space radiation effects should occur from unavoidable – or accidentally high – radiation exposures, mitigation of these effects will have to rely on pharmacological measures, i.e., the administration of therapeutic and – preferably – prophylactic radioprotective drugs. The performance of 'heroic' surgical therapeutic measures, such as bone marrow transplantation, will not be feasible for the present, and most likely in most future, scenarios.

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Table 4.7: Compilation of dose reduction factors (DRF) of aminothiol compounds providing significant protection against early radiation sequelae in animal model systems
From: Giambarresi and Jacobs, 1987

Compound	Aminothiols[a] Toxic[b] LD50 (mg/kg)	Protective[b] dose (mg/kg)	DRF
Cysteine	1700	1200	1.7
MEA	200	150	1.7
Cystamine	220	150	1.7
AET	480	400	2.1
WR-638	1120	500	2.0
WR-2721	950	500	2.7
WR-3689	1120	450	2.2
WR-77913	3574	2200	2.0
WR-151327[c]	785	315	1.9
Mercaptopropionylglycine[d]	2100	20	1.4
Glutathione	4000	4000	1.3

[a] *Data taken from $LD_{50/30}$ studies using mice exposed to X- or gamma radiation.*
[b] *By ip injection except for cysteine, which is by iv injection.*
[c] *Provides substantial protection against neutron irradiation.*
[d] *Provides significant protection when given after irradiation.*

Among the most potent groups of free radical scavenging chemicals, the class of aminothiols has been studied most intensively and the results of thousands of, mainly animal model, experiments are condensed in Table 4.7. It summarises the protective efficacy of the most promising aminothiols in terms of their dose reduction factor, DRF, which specifies the factor by which a radiation dose can be enlarged under administration of a given substance until the same early response level is reached that occurs without protection by this substance. With the most potent of these substances, the drug WR-2721, a DRF as large as 2.7 was found in animal experiments at the highest tolerable medication doses. All human organs, other than nerve tissue, respond to its protective action. The protective action of all of these substances is, however, restricted to a rather short time window around the irradiation event and practically all of them have to be administered prior to irradiation for their protective action to work. In addition, the pharmacological side effects engendered at therapeutically effective doses often closely resemble the symptoms of the prodromal radiation syndrome from which these substances should be protecting the exposed personnel. Information regarding these side effects has been gained from human exposures, in the context of radiation therapy where such substances are applied in order to differentially increase the tolerance of normal tissue that might be affected by stray radiation from the irradiated tumour tissue in its vicinity. These side effects essentially prevent the application of these substances in the context of space radiation protection and, apart from the most unlikely – although not impossible – accidental event of irradiation by a 'killer' SPE outside a shelter, radiation doses as large as those involved in tumour therapy will not be encountered.

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Table 4.8: Compilation of non-aminothiol radioprotective compounds, as classified according to their putative reaction mechanisms. From: Giambarresi and Jacobs, 1987

Radioprotective Compounds[a]

Compound	**Protective effect**[b,c]	**Probable mechanism of action**
Sulphur-containing compounds		Free-radical mechanisms
Diethyldithiocarbamate (DDC)	3	Complex
Dimethylsulphoxide (DMSO)	2[d]	
Thiourea	1	
Cyanide derivatives[e]		Hypoxia
Cyanide	2	
Hydroxyacetonitrile	3	
Malononitrile	2	
Chelating agents		Uncertain
EDTA	1	
Metabolites		Free-radical scavenging
Glucose	1[f]	
Fructose	2[f]	
α-Ketoglutarate	1	
Hypoxia inducers		Hypoxia
Paraminopropiophenone	3	Haemoglobin chang
Carbon monoxide	2	
Ethanol	2[f]	Respiratory centre depression
Morphine	2	
Reserpine	2	
Serotonin	3	Haemodynamic alteration
Histamine	2	
Immunomodulators		Haemopoietic system recovery
Glucan	1[g]	
Endotoxin	1[g]	
Azimexon	1[g]	
Levamisole	1	Complex
Antioxidants		Free-radical mechanisms and oxygen metabolism
Vitamin E	1[h]	
Vitamin A (ß-carotene)	1	
Superoxide dismutase	3	
Selenium	1[h]	

a Aminothiols are presented in Table 4.7
b Data taken from studies using mice exposed to X- or gamma radiation.
c Grading is according to following scale:
1, slight protection (DRF <1.2);
2, moderate protection (DRF <1.5);
3, good protection (DRF >1.5).
d Provides protection when administered topically
e Highly toxic: Protective dose is very close to toxic dose.
f Provides proteciton only at extremely high doses: glucose and fructose, 13,500 mg/kg; ethanol, 6-7.4 ml/kg.
g Provides protection when administered after irradiation.
h Provides protection when given orally

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Among non-aminothiol radioprotective substances, dose reduction factors of up to 3 have also been found (Table 4.8), some of which may be protective even if administered after irradiation. Among those, the 'immunomodulating' compounds that support recovery from damage to the haemopoietic system may be candidates for therapeutic drugs to be administered after accidental SPE irradiation, although their protective efficacy is rather moderate (DRF<1.2). In general, however, their application in space is again hampered by the rather pronounced toxic side effects that they exhibit at therapeutically effective doses. The further search for effective radioprotective chemicals with less severe side effects finally led to the discovery of several new classes of compounds which, for the first time, offer some potential to protect also against the late health effects from ionising radiation, i.e., against carcinogenesis. Table 4.9 includes naturally occurring biochemicals instead of the preponderance of synthetic compounds found in the earlier compilations. The antioxidative compounds hold an important position among these substances. Since many of these compounds occur in significant concentrations in natural food (Table 4.10) these recent findings offer, for the first time, a prospect of successfully utilising such radioprotective substances for space radiation protection, simply by optimising dietary supply during the mission. Whereas dietary control of tissue/cellular concentrations of enzymes and other proteins of the antioxidant defence system is limited, phytochemical antioxidants are affected more directly by the amount and composition of the diet and its supplementation with food derived from the appropriate plants.

Of course, the universal caveat applicable to all assessments of space radiation hazards has to be raised in this context as well. To the extent that these experimental findings have been obtained with comparatively sparsely ionising radiation under normal terrestrial gravity conditions, the transferability of these results to the space radiation environment depends on the empirical verification that neither the drastically different radiation qualities nor the specific exposure conditions – including but not restricted to microgravity – alters the mechanisms involved and so reduces the applicability of the terrestrial findings.

4.2.8 Recommended research into radiation health issues

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

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

Research recommended into radiation risk assessment

In order to obtain accurate and reliable estimates of the risks associated with exploratory space activities, the first task is to adopt a measure of risk suitable for

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Table 4.9: Compilation of results obtained in recent studies into cellular and molecular radioprotective mechanisms of chemoprotective compounds. From: Stanford and Jones, 1999.

Bioantimutagens	
Vanillin	Enhance postreplication recombinational repair
Protease Inhibitors	Inhibit error-prone repair induced by proteases
N-Acetyl-L-Cystejne	Increase level of DNA repair
Desmutagens	
Inhibit Carcinogen Formation	
Polyphenols	Deactivate/detoxify carcinogens
Isothiocyanates	Affect nitrosamine metabolism
Antioxidants	
Scavenge Reactive Electrophiles	
NAC	Electrophile scavenger
Ellagic Acid	Glutathione S-Hydrogenase activity enhancement
Allylic Sulphides	GSH enhancer
Scavenge Oxygen Radicals	
Thiols	React with hydroxyl radicals
ß-Carotene	Interacts with singlet oxygen
α-tocopherol	Scavenge peroxy, singlet oxygen, superoxides
Superoxide Dismutase	Destroys superoxide radicals
GSH Enhancers	GSH reacts with alkyl-peroxy radicals, flavanioids, polyphenols
Alter Arachadonic Acid Metabolism	
Aspirin	Cycloxygenase inhibition, prevent reactive species
NSAIAs	Cyclooxygenase inhibition, inhibit Phospholipase C
Flavanoids	Cyclooxygenase inhibition, inhibit lipoxygenase and free radical production
Curcumin	Inhibit lipoxygenase and free radical production
Polyphenols	Inhibit lipoxygenase and free radical production
Antiproliferatives/Antiprogression	
Modulate Signal Transduction	
Flavanoids	Inhibit Protein Kinase C (PKC)
Glycyrrhetinic Acid	Inhibit PKC
Modulate Growth Factor (GF) Activity	
Tamoxifen	Increases Transforming GF ß, decreases IGF
Diminish Oncogene Activity	
Genestein, Quercetin	Inhibit tyrosine kinases
Monoterpenes	Inhibit *ras*, G-protein farnesylation
Stimulate or Restore Tumor Suppressor Function	
No proven agents currently	
Inhibit Polyamine Synthesis	
DFMO	Inhibit Ornithine Decarboxylase (ODC)
Retinoids, Tamoxifen	Inhibit ODC induction
Correct DNA Methylation Problems	
Folic Acid	Regulates intracellular methyl metabolism
Induce Terminal Differentiation	
Retinoids	Affect binding proteins
Calcium + Vitamin D3	Act on nuclear receptor
Restore Immune Response	
Selenium	Increased NK cell killing of tumor cells
Vitamin E Retinoids	Immune stimulants
NSAIAs	Inhibit CyOx and PGE_2 production
Increase Intercellular Communication	
Retinoids, ß-carotene	Affect gap junctions
Induce Apoptosis	
Genestein, Retinoids, Tamoxifen	Initiate programmed cell death

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Table 4.10: Food with significant concentrations of naturally occurring radioprotective compounds (From: Stanford and Jones, 1999)

Allium and N-acetyl cysteine (Diallyl sulphide)	Onions, garlic, chives, scallions
Sulphoranes and Isothiocyanates (Dithiolthiones and Thiocyanates)	Cruciferous vegetables (e.g., broccoli, cauliflower)
Isoflavones and Phytoestrogens	Soya beans
Terpenes and Ascorbic Acid (perillyl alcohol, limonene), lycopene	Citrus Fruits (particularly the peel) lemons, tomatoes
Curcumins	Tumeric
Carotinoids, antioxidants	Yellow vegetables, fruits (e.g., carrots, squash)
Polyphenols and Flavonoids (EGCG, Phenolics, Thearubigens, Theaflavins)	Green and black teas, fruits, red wine

exploratory missions, which should integrate the assessment of radiation risks into overall mission risk management. This task should enable a unified treatment of risks from any source, so as to minimise – within the constraints of the mission's objectives – the expectation value of Healthy Lifetime Lost (HLL) due to the mission. This approach would identify the repercussions on the overall probability of mission success of design measures to counter radiation hazards, for the vehicle, habitat, shielding, and equipment, as well as the risks stemming from radiation-induced malfunctions of equipment.
In order to achieve this goal, research is recommended, dedicated to the solution of the following problems:

- Establish distribution functions for the exposure (dose) from solar particle events for a mission, with a given habitat shielding distribution, of a given duration, during a given phase of the solar cycle. A solution to this problem requires fundamental advances in solar/stellar physics. Until then solar observational programmes should be as comprehensive as possible, in order to broaden the empirical basis and sample size used for stochastic extrapolation.
- Determine dose response functions for early radiation sequelae appropriate for solar particle radiation, including dose rate effectiveness factor and potential modification by the spaceflight environment. A review of published early side effects, as observed in the course of radiation therapy with protons, could possibly yield quantitative data regarding some of these response functions and their modification by various fractionation schemes.
- Determine the probability of 'fatal' crew performance reduction due to early radiation effects, as a function of radiation dose and time after exposure. A review of studies concerning the time course of the performance reduction of combat personnel in the nuclear battlefield and the integration of these data into an Integrated Performance Modelling Environment (see Chapter 6) could possibly yield such data.
- Improve and validate transport codes for the prediction of solar particle and cosmic heavy ion radiation doses inside a given shielding distribution, at a given position in interplanetary space, at a given time within the solar cycle. Despite the substantial advances achieved for radiation environment modelling and transport codes, significant further improvements are needed regarding the

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description of the radiation field within a given organ, not only in terms of absorbed dose or equivalent dose, but also – preferably – in terms of the charge and energy distribution of its constituents, including the significant neutron component within heavier shields or on planetary surfaces. Measurement campaigns on the ISS form the ideal tool for experimental validation of radiation environment models, of transport code algorithms and reaction cross sections. Improvement of the database of the latter depends on further theoretical and experimental work on high-energy fragmentation with accelerators. Measurements on the lunar surface or in lunar habitats would provide more sensitive tests regarding the more important neutron contribution. Currently the human phantom *Matroshka*, with suitable radiation detectors at the position of critical organs, is under construction for use as a facility for validation of dose prediction calculations during extra-vehicular activities. As noted previously, an indispensable requirement for achieving this goal is the complete characterisation of the response functions of the detection devices used. This in turn would require dedicated irradiation campaigns with accelerated heavy ions and the corresponding theoretical work. Such joint international proposals, also involving members of the WRMISS (Workshop on Radiation Monitoring of the International Space Station), are presently being negotiated for submission in the frame of NASA's Radiation Health and Flight Research programmes. Since the WRMISS was founded, and is guided, by European investigators – see www.magnet.oma.be/wrmiss/wrmiss.html – and since the development of *Matroshka* is funded by ESA, such proposed activities would be among the few cases where European excellence in manned spaceflight is clearly evident.

- Establish the probability for cancer mortality (morbidity) for a given tissue, as a function of total radiation exposure during the mission and as a function of time after the mission. For the contribution from SPE (mainly protons) some quantitative data may be extracted from published late effects observed subsequent to radiation therapy with protons. For the contribution from GCR, irradiation experiments at heavy-ion accelerators with mammalian cells – preferably *in vivo*, i.e., in animal models – will yield relevant empirical data, provided the experiments are performed at appropriately low fluences as, for example, in the recent experiments at microbeam facilities. In this case, the European facilities at GSI, Darmstadt and at GANIL, Caen can provide appropriate irradiation opportunities. The validity of the transfer, that would be required, of animal data to human exposures, can only be assessed after sufficient theoretical insight has been gained into the mechanisms which link the initial physical events of energy absorption with the final pathological condition. More accurate knowledge of the true response function for cancer induction at low exposure levels (single particle traversals) could significantly impact the costs involved in complying with terrestrial radiation protection regulations – at least for uranium mining. These will, of course, be more restrictive, and expensive, the higher the worst case estimate of the risk. Indeed, this association provided the decisive impetus for the initial development of the microbeam techniques. Related R & D activities in this field are thus strongly correlated with terrestrial applications.
- Investigate the applicability of terrestrial dose response functions for prediction of the response to radiation exposure under spaceflight conditions (early effects from SPEs, late effects from SPEs and GCR). This can only be achieved by experimental studies on the ISS and possibly on a lunar base. Regarding the indispensable investigations on animals, a precursory feasibility study should identify to what extent the requirements that are needed for useful results can

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be met. The importance of this problem justifies the proposal to integrate into the operational medical surveillance of the ISS astronaut corps a measurement programme which specifically checks for as many known radiobiological effects as possible at the molecular, cellular, and tissue levels. Comparison of such quantitative biological data with predictions from the physical dosimetric record could help to determine at least upper bounds for the dose modifying factor(s) potentially associated with the space exposure conditions.

Research recommended into radiation surveillance

Monitoring of the actual radiation exposure during the course of a mission serves a twofold purpose: firstly, it provides a quantitative measure of the actual risk – strictly speaking of the actual exposure – already incurred in the cases where unforeseen events call for operational decisions regarding its further course; secondly, if unexpected medical conditions were to transpire after the mission, an adequate dosimetric record would allow the role of the individual radiation exposure in the phenomena observed to be assessed. This would eventually improve our capability to predict such effects. To reach an adequate level of radiation monitoring during exploratory type missions, the following activities are recommended:

- Improve SPE forecasting to ensure that there is sufficient time to reach shelter in every mission phase. Experimentally this includes the continuous extension and refinement of solar observational techniques and the further expansion of the monitoring systems that already cover interplanetary space for space weather forecasts. Theoretical progress in modelling solar physics is required in order to improve forecasts beyond the state of purely phenomenological probabilistic extrapolation.
- Design particle telescope detector systems for charge and energy resolved (online) flux monitoring, including – in particular – provisions for regular (re) calibration. The ensemble of dosimetric instruments for monitoring the radiation environment on ISS is a proper prototype for the given mission scenarios. Quality assurance and maintenance measures, which for the ISS can draw on terrestrial support, must, however, be performed without this support and this is the major development task.
- Design passive (visual track) detector stacks for measuring accumulated heavy ion fluences. Again the detector systems used on ISS may be used for an initial design. The sensitivities or detection thresholds, as well as the (chemical) stability of detector materials, must be adapted to withstand the long duration and to match the dynamic range to the expected total particle fluences.
- Adapt terrestrial equipment and procedures for surveillance of haematological and immunological radiation effects to flight conditions.
- Develop techniques for scoring chromosome aberrations during the mission. The adaptation of terrestrial sample handling to the absence of gravity and the automation of the scoring process by means of automatic image analysis are the major development tasks for the previous two activities. Though by no means trivial, no fundamental obstacles are discernible, so this will consist mainly of technology development.
- Develop bio-analytical techniques to monitor oxidative stress during the mission. Since the last three biological surveillance measures require the taking of blood samples or other ‘invasive’ procedures, the question of whether such ‘injuries’ are at all compatible with medical safety requirements and, if so, at what intervals, has to be settled before major development efforts are undertaken. Therefore, complementary to endogenous biomarkers, the development of exogenous bioassays will be necessary (Horneck, 1998). In addition to their environmental monitoring function, these techniques will be

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necessary for, or at least instrumental in, verifying the effectiveness of radioprotective medication/nutrition countermeasures in, for example, the ISS crew.

Research recommended into countermeasures against radiation effects
Countermeasures in radiation protection have to resort to mitigating the severity of the consequences of radiation exposure by reducing radiobiological sensitivity towards late effects or by reducing the severity of acute symptoms of early effects. To achieve this, the following research is recommended:

- Determine the limits of medically feasible invasive treatment in the case of severe accidental overexposures from solar particle radiation. Although 'heroic' measures such as bone marrow transplants have been ruled out, terrestrial treatment schemes for acute radiation sickness should be scrutinised to see where the limit should be drawn for space.
- Screen standard medicines that are already part of the onboard medical support system, to see whether they have radioprotective efficacy. For example, symptoms of the prodromal syndrome occur in many other pathological conditions so that at least symptomatic palliative treatment would be possible with such multi-purpose drugs. In contrast to the treatment of the symptoms of early effects after acute (SPE) irradiation, the following measures are prophylactic insofar as they increase the resistance of crew members – mainly against late effects. This can be achieved by chemoprotection, by selection of individuals with higher, genetically determined, resistance, or by exploiting adaptive response.
- Optimise dietary input to minimise oxidative stress. The findings that (a) reactive oxygen species (ROS) are instrumental in carcinogenesis, (b) reactive oxygen species and other free radicals are part of the chain of reactions linking initial energy absorption with radiobiological effects, and (c) the oxidative status in humans is shifted towards higher stress during spaceflight, make this approach appear the most promising countermeasure presently available. In the pursuit of this goal, terrestrial 'analogue' studies in human volunteer populations will certainly be a necessary preparatory stage to optimise study design and analytical procedures. In such experiments the influence of the increase of oxidative stress with age should also be examined. The final proof of the effectiveness of these measures can only be established by verification of such results in the space crew, the ISS crew naturally being the first choice. Finally – apart from activities related to radiation health in space missions, positive results from such research could be beneficial for terrestrial applications, e.g., in cancer prevention by nutritional means.
- Study intra- and inter-individual variation of tissue radiosensitivities. Determination of the radiosensitivity of different normal tissues is established – though not yet common – in radiation therapy of cancers, so techniques applied for that purpose could be used to screen space crew applicants too. These tests require the drawing of biopsies from organs, (at least from skin) to determine the sensitivity to cell killing under the proposed treatment plan. The benefits that might be gained are, however, limited. Most importantly, the resistance to cell killing would only be predictive of the susceptibility to early effects from acute SPE irradiation, exposure to which would normally only be considered to occur by accident. Furthermore it has yet to be determined to what extent findings for one tissue can be generalised to others of the same individual, notwithstanding the fact that this is often tacitly assumed. Finally, among the selection criteria for crew of exploratory missions such as the scenarios considered here, other criteria are likely to dominate the final

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selection, so that the selective power of these tests for sensitivity to early effects might not merit the risks inherent in taking the tissue samples.

- Complementary to cell killing, the induction of a transformed phenotype (foci) in cells cultured from biopsies – so called cell transformation – is a biological endpoint which is considered as rather closely related to carcinogenesis, so that findings from such studies could be used as more reliable indicators of susceptibility to radiogenic cancer induction. This higher 'prognostic' power is countered by the enormous experimental effort – materially and in terms of time – needed to obtain sufficient statistical precision. Yet, given an otherwise pre selected population of 10 or 20 candidates the feasibility of such assays merits further scrutiny.
- Scoring for genotoxic effects in peripheral lymphocytes conceptually yields results less closely associated with (solid) tumour induction than cell transformation. However, sensitivity for induction of chromosome aberrations or of micronucleus formation is already being studied as a tool to investigate inter-individual variability of radiosensitivity and so these techniques should be considered as candidates for crew screening criteria.
- The techniques discussed here have a rather long history of successful application. The additional effort would mainly consist of technological modifications that would render results with sufficient accuracy to be useful as a screening criterion.

- Search for genetic 'markers' that are predictive for reduced cancer induction. In contrast to the foregoing R & D activity, the techniques available for studying genetic markers are at the cutting-edge of biological research. Essentially they allow the identification of 'gene expression patterns' by comparing genetic material from tissue samples with 'fingerprints' of known genetic constitution. The breathtaking speed of molecular-genetic research has already made available defined 'fingerprints' as 'off-the-shelf' products. Such "DNA micro arrays" or "DNA chips" are already applied – though not yet routinely – in cancer therapy, to identify and localise the 'mother-tumour' by genetic classification of tumours of suspected metastatic origin. Screening for reduced concentration/activity of mRNA of tumour suppressor genes, e.g, *p53*, or for increased concentration/activity of mRNA of oncogenes, for example, *ras* or *myc* genes, would identify candidates with higher susceptibility for spontaneous (and putatively also for radiogenic) carcinogenesis – and *vice versa*.

  - Such investigations can be performed with primary cells. Usually, circulating peripheral cells or skin fibroblasts are studied. To what extent results obtained with these cells can be generalised to other tissues of an individual has yet to be determined. However, concerning findings for which – with due consideration of the ontogenetic stage – the genetic background can clearly be elucidated, e.g. the involvement of tumour suppressors or oncogenes, it is likely that they pertain to all tissues and hence to the whole individual.
  - The last three activities have potentially significant impact on cancer research, for example, regarding improved, or more precisely targeted, preventive diagnostic screening, as well as more precisely tuned therapeutic efforts

- Research into mechanisms of adaptive response or induced resistance to ionising radiation. In contrast to the previous research activities, our present

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knowledge regarding this phenomenon relies mainly on cellular model systems. Whether the augmented radiation resistance inducible by appropriate low-level pre-irradiation remains effective also *in vivo* at the tissue or organ level is the first question that has to be resolved by appropriate animal studies. Further studies that address the question whether dose rates in space fall into a range where the adaptive response is still beneficial would only be warranted if the gain in resistance were significant. Notwithstanding the (unlikely) applicability of artificial low-level irradiation to induce increased resistance, the possibility that dose rates in space at least partially fall into this range, merits closer investigation. Positive results with respect to the previous four research activities might reduce the risk estimates sufficiently to ease the constraints imposed on mission design by radiation protection constraints.

- Verify the transferability to heavy ions and space exposure conditions of ameliorative measures obtained with sparsely ionising radiation. Since most, if not all, of the experimental work related to radioprotective measures will initially be performed under terrestrial conditions and with common terrestrial sparsely ionising sources, the standard caveat applies again: the transferability of these results to the space radiation environment depends on the empirical verification that neither the drastically different radiation qualities nor the specific exposure conditions – including, but not restricted to, microgravity – alters the mechanisms involved.

4.3 Microgravity, reduced gravity and general health issues

4.3.1 Introduction

The transition through various levels of gravity, such as from 1g through hypergravity to microgravity during launch, long-term exposure to microgravity during interplanetary transfer, transition from microgravity to hypergravity during de-orbiting and stay at reduced gravity on the celestial body (Figures 2.3 and 2.6) – to mention just one half of the round-trip to the Moon or to Mars – have major implications for astronaut health control. This concerns deconditioning symptoms, such as loss of muscle and bone mass, reduced cardiovascular and physical capacity and changes of motor skills (Figure 4.12). In addition to this gravity-related risk for astronauts on planetary missions there is an inevitable risk of other illnesses, which would occur anyway during any long-term absence from home facilities. This latter risk is especially severe for missions to Mars, from which fast emergency return to Earth is impossible. Crew health and performance have to be ensured during transfer flights, during planetary surface exploration, including EVAs, and upon return to Earth, within the constraints of safety objectives and mass reduction (see Chapter 3). Thus, before the design of an exploratory mission (hardware and operations) as defined in Chapter 2, numerous issues in life sciences need to be addressed.

4.3.2 Gravity-related crew health challenges

It is well known that unrestricted adaptation to microgravity leads to physical deconditioning, such as loss of muscle and bone mass (Heer et al., 1999), reduced cardiovascular and physical capacity, and changes in motor skills (Moore et al., 1996). From both ethical and medical points 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 an 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

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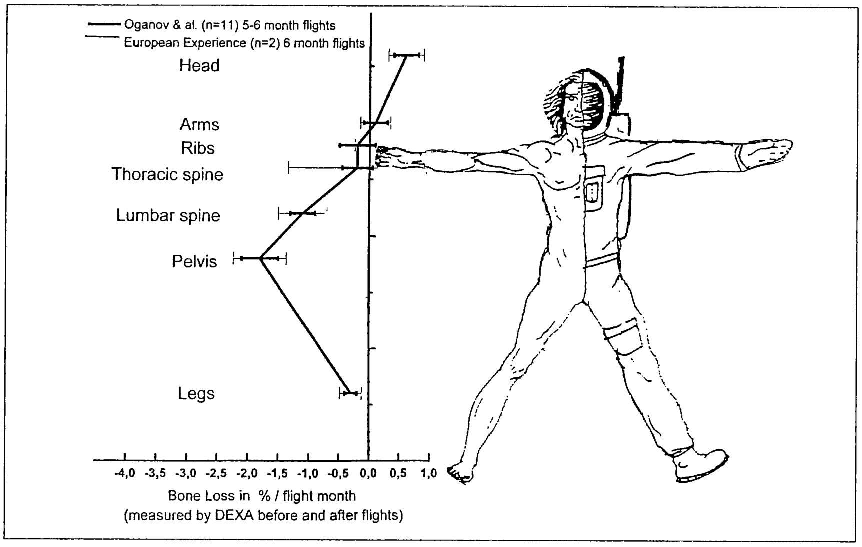

Figure 4.13: Microgravity-induced changes in regional mineral bone density, given as change in mineral bone density in percent per month flight (adapted from Oganov et al., 1991; 1992; Oganov & Schneider 1996; Daphtary et al., 2000).

deconditioning observed in elderly people, can be life threatening, especially in emergency situations, or during EVAs on a planetary surface that involve physically intense work.

Microgravity-induced musculo-skeletal disorders
The estimated probabilities of musculo-skeletal disorders induced by microgravity or reduced gravity during the three mission scenarios are summarised in Table 4.11. Using the Mir station, the changes in regional mineral bone density were measured on 11 cosmonauts before and after the spaceflight of 5-6 months duration (Oganov et al., 1991; 1992; Oganov and Schneider 1996; Daphtary et al., 2000). Figure 4.13 shows the topography of bone loss during spaceflight. The mineral bone density is given in percent per month of spaceflight (DEXA method). At the level of the pelvis, the rate of bone loss reaches 1.35 to 2.0% per month of spaceflight; at the level of the femoral neck the loss rate has been measured as 1.16%, and at the level of the femoral trochanter as 1.58% per month of spaceflight. One has to bear in mind that these data were obtained from cosmonauts and astronauts that employed countermeasures during the spaceflights, such as wearing the "penguin suit" and performing physical exercise twice per day. Extrapolating from these results, for example for Scenario 2 with a 1000 day space mission, the level of bone density loss could reach 38% at the level of the femoral neck and up to 50% at the level of the femoral trochanter. These levels far exceed the threshold for significant risk of fracture, which is a bone loss rate of 15%. For that reason, bone demineralisation during spaceflight still remains an unacceptable and uncontrolled risk, especially for long-term missions, such as Scenarios 2 and 3 to Mars.

The muscular impairment induced by microgravity is characterised by structural and functional changes. There is a loss of muscle mass mainly at the level of the legs and trunk. The muscle loss at the level of the soleus has been quantified as 0.6% per day during a 35 day Mir mission (Jaweed, 1994). Analysis of muscle biopsies before and after flight has shown a decrease in the number of Type I muscle fibres and no significant changes in Type IIA and IIB muscle fibres. It was

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concluded that the exposure to microgravity decreased the oxidative potential of the muscle. From studies of muscle function it was found that the muscle force was decreased (with individual differences), and muscle fatigue (as a ratio of initial force to fatigued force) was increased (Jaweed, 1994; Greenisen et al., 1999; Bodem et al., 2000). Some motor control changes have also been reported. The thresholds for evoking the T- and H-reflexes were lower after spaceflight than before (Koryak et al., 2000). It is important to note that the astronauts who exercised during spaceflight had less muscle impairment after flight than those without exercising (Jaweed, 1994).

Back pain has been reported during spaceflight, although the mechanism is not fully explained (Wing et al., 1991; Baum et al.,1997).

Microgravity-induced neurosensory disorders
Knowledge of neurosensory and cognitive responses to microgravity has greatly expanded during the last twenty years. The space adaptation syndrome resulting from the neurosensory and cognitive responses to the transfer from 1g to microgravity, or from microgravity to a 1g environment, and probably to 0.16g for the Moon or 0.38g for Mars (planetary adaptation syndrome), is an impairment of the crew performance which is increased by the side effects of medication. It impairs the performance of the astronauts, but its adverse consequences, such as nausea and vomiting, may be controlled pharmacologically and by limiting activity during the adaptation period. This impairment persists for about three days, representing the duration of the neurosensory adaptation (Reschke et al., 1994a,b). After long duration space missions (up to six months), the sensorimotor alterations are greater and persist longer (up to three days) than after short duration missions (less than one month) (Palowski, 1998). Current data indicate that significant disorders occur during the adaptation periods, with the most visible being the space or planetary adaptation syndrome which is most serious when arriving in microgravity, and probably also when arriving on a planet (Earth, the Moon or Mars). These responses are often the same when returning from microgravity to normal gravity and probably also to reduced gravity. Concerning the adaptation to reduced gravity, the only data available are from the Apollo lunar missions and no significant neurosensory disorder was reported during the exploration on the surface of the Moon. However, the Apollo missions were of short duration (the maximum duration was the Apollo 17 mission, which lasted for 12.5 days, including three days on the lunar surface). The disorders found after the Apollo flights were probably more induced during the Earth to Moon transfers in the microgravity environment than by the lunar exploration itself under 0.16 g. In the clinical reports of the Apollo missions (Apollo 12, 14, 15, 16 and 17), no hypotension syndrome or motion sickness were reported after landing on the Moon's surface (Hawkins & Zieglschmid, 1975); however motion sickness was reported after arrival in orbit and hypotension syndrome was reported after return to the Earth.

The estimated probabilities of neurosensory disorders induced by microgravity or reduced gravity (0.16g on the surface of the Moon and 0.38 g on that of Mars) occurring during the three mission scenarios are summarised in Table 4.11.

Microgravity-induced orthostatic intolerance
During the last fifteen years, our knowledge of the cardiopulmonary response to microgravity has expanded greatly. The fluid shift in the human body, induced by microgravity, provokes appropriate adaptation to the microgravity environment, for example by reduction of the plasma volume. When returning to 1g, the reduced body fluid volume contributes to the orthostatic intolerance (Charles et al., 1994). This post-

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Table 4.11: Probabilities of gravity-related disorders during the three mission scenarios (in %)

Gravity related effect	**Scenario 1** 180 day Moon mission		**Scenario 2** 1000 day Mars mission		**Scenario 3** 500 day Mars mission	
	On board the transfer vehicle	On Moon Surface	On board the transfer vehicle	On Mars Surface	Onboard the transfer vehicle	On Mars Surface
Bone demineralisation (this disorder is considered unacceptable when the bone loss is >15% (DEXA measurement), when the bone fracture risk is significant)	AR *	Unknown	6	Unknown	6	Unknown
The exercise capacity impairment (due to muscular and cardiovascular deconditioning) is considered unacceptable when > 20% compared with the preflight level	AR *	Unknown	6	Unknown	6	Unknown
Back Pain	2	Unknown	3	Unknown	3	Unknown
Space and "planetary" adaptation syndromes	6.4	3.2	8	3.2	8	3.2
Orthostatic intolerance	0	0.024	0	0.024	0	0.024

** AR = Accepted Risk because the probability of occurrence is too low (< 0.001)*

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flight orthostatic intolerance appears also to result from changes in the central modulation of baroreceptor inputs (Charles et al., 1999). Subjects having lower norepinephrine levels, and lower peripheral vascular resistance when standing (before and after flight), are more susceptible to post-flight orthostatic intolerance (Charles et al., 1999). Even though the duration of post-flight orthostatic intolerance increases with the duration of the preceding spaceflight, the orthostatic tolerance (without countermeasures) is reversed within 3-4 days (even after a six month spaceflight) (Yelle, 1998). It has been further found that microgravity-induced changes in the pulmonary function have no clinical significance for crew (Charles et al., 1994).

The estimated probabilities of occurrence of orthostatic intolerance (using adequate countermeasures) induced by the microgravity or reduced gravity during the three mission scenarios are summarised in Table 4.11.

Attempts to simulate reduced gravity effects
Numerous methods have been proposed or used to simulate reduced gravity, essentially to study motion behaviour and metabolic rate in subjects while egressing and landing (Simons et al., 1965; Sanborn et al., 1967). These methods, such as vertical motion devices or vertical cable suspensions, do not, however, simulate cardiovascular adaptation, the neurosensory adaptation, or the musculoskeletal impairments (Davis et al., 1993). Parabolic flights, including lunar gravity manouevres did not last more than 30 seconds (Simons et al., 1965). Reduced gravity acts on the cardiovascular system mainly because of the loss of the hydrostatic pressure gradient, on the musculoskeletal system by the reduced loading on the weight-bearing structures (bone and muscle), and on the neurosensory system by a reduction of gravity-dependent sensory inputs.

A relatively successful cardiovascular simulation of a lunar mission has been achieved using the following model: four days in a position of head down tilt (HDT) (-6°) (to simulate the effects of microgravity during the transfer), six days in a position of head up tilt (HUT) of +10° (simulating the lunar hydrostatic pressure at 0.16g), and again during four days in a position of HDT (-6°) (to simulate the effects of microgravity during the transfer). No differences were noted with the classical cardiovascular microgravity deconditioning (after long and short duration spaceflight) (Pavy Le Traon et al., 1997). Otherwise, little information is available on human disorders induced by short or long exposure to reduced gravity (0.16g and 0.38g), because simulation of such levels of gravity is not easy on ground, and the flight data from the Apollo missions concerned only short (three days maximum) exposure to 0.16g (MEDES, 1992).

4.3.3 General crew health challenges

There is a significant probability of diseases and injuries occurring during a 500 day or 1000 day Mars exploration mission, as defined in Scenarios 2 and 3. This is especially severe, because an emergency return is impossible and, with a one way tele-transmission delay of 20 minutes, a real-time telemedicine system will not be effective. Therefore Mars exploration missions will bring several major challenges for the life sciences, as identified in Section 3.3.

For the Moon mission (Scenario 1) the problems are less critical because an emergency return within some days is possible, the telemedicine system will be very effective (no significant delay of tele-transmission), and most diseases with a significant probability of occurrence can be prevented or treated using medical facilities similar to those used on Mir, and available or planned for ISS.

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Control of infectious diseases
Studies on the human immune system during spaceflight have shown that human T-lymphocyte activation by concanavalin A is inhibited by 93% during exposure to microgravity, probably due to a malfunction of monocytes acting as accessory cells (no InterLeukine I production in microgravity). The activation of Jurkat cells is also severely impaired by the space environment. (Cogoli et al. 1984; Cogli & Tschopp, 1985; Cogoli, 1993). It has been further demonstrated, on Rhesus monkeys, that the expression of InterLeukine II receptors is decreased by the space environment (Sonnenfeld et al. 1996; Walther et al., 1999). However, when attached to Cytodex, human T-lymphocytes double their activation in microgravity when sufficient InterLeukine I is available in the medium (Belcher et al., 1992). Furthermore, the distribution of the protein kinase C is altered in microgravity compared to 1 g conditions (Schmitt et al., 1996).

From medical observations of the astronauts and cosmonauts it is known that most infections (mainly of the upper respiratory tract) happen early in a space mission (Pierson, 1994; Billica et al., 1994) with a mean incidence of 6 per person and year. This number agrees very well with our estimated incidence of 6.2 per person and year. After short flights, natural killer cell activity decreased or stayed in the normal range, but decreased by 60-90%, in three of twelve subjects, after 112-175 days of spaceflight. It was found that the cosmonauts' lymphocyte counts stayed in a normal range during flights of 75-185 days duration, but the T-cell number was decreased (Konstantinova, 1991; Legenkov & Kozinets, 1996). From measurements of cutaneous hypersensitivity it was concluded that the cell-mediated immune response decreases until flight day 5, and then recovers during the following days in space (Pierson, 1994). After return from spaceflight, the immune system competences are recovered within seven days. The immune system reaction tests performed during the NASA-Mir missions (measurement of serum immunoglobulin levels, assessment of the immune cells' ability to produce appropriate antibodies in response to specific antigens, measurement of IgA and lysozyme in saliva, and evaluation of the responsiveness of immune cells to polyclonal activators) have not revealed any immune suppression after flight (Sams & Lesnyak, 1998). So far, it has not been established clearly what factors are responsible for immune suppression – stress, confinement, microgravity, or space radiation.

Concerning antibiotic resistance, some bacteria (*Escherichia coli* and *Staphylococcus aureus*) have been found to be more resistant to antibiotics in space than on Earth (Tixador et al., 1985; Moatti et al., 1986). This finding may indicate a need for a higher antibiotic dosage in space than on the ground. In this context, more pharmacodynamic data on humans during flight are required, taking into account fluid shifts and absorption and elimination changes induced by microgravity. During NASA-Mir missions, contradictory results have been obtained with significantly increased or decreased resistance to antibiotics, depending on the nature of the bacteria and the type of antibiotics (Klaus, 1998). Furthermore, the risk of increased antibiotic resistance of pathogenic microorganisms, for instance induced by space radiation (Horneck, 1992; Kiefer et al., 1996) should not be neglected.

Up to now all the studies performed during flight have shown that the main sources of microbial contaminants are the crew members themselves (Pierson, 1994). The studies performed during long duration flights have revealed that the commensal flora of the crewmembers were uniform, probably due to the close

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confinement. During the NASA-Mir missions, the findings from the microbial samplings of the crew during and after flights did not reveal any anomaly; the composition and amount of the microflora were consistent with that of healthy individuals. In one example, an exchange of the potentially pathogenic ***S. aureus*** has been observed between a crew member and the cabin environment. (Pierson & Viktorov, 1998; 1999).

The estimated probabilities of infectious diseases occurring during the three mission scenarios are summarised in Table 4.12.

For the diagnosis and treatment of infectious diseases, techniques have been developed for utilisation in space, such as blood cell counts and urinary analysis (urinary sticks). For human exploratory missions, especially to Mars, these techniques will have to be further developed to allow bacteriological sampling, culturing, antibiograms, and bacteriological urinary analysis. Compact X-ray equipment will hopefully be available for the manned exploratory missions, to assist diagnosis of infectious diseases and also for other diseases and injuries.

Control of neoplasm risk, and endocrine, nutritional and metabolic disorders
A major haematological alteration, and reductions of the plasma volume and of the red cell mass occur during spaceflight, with a new equilibrium quickly being reached – within approximately two weeks – during long duration flights (Leach-Huntoon et al., 1994; Legenkov & Kozinets, 1996). As a consequence of these haematological adaptations to microgravity a relative anaemia was observed after spaceflights, but recovery occurred within two weeks as a result of erythropoiesis, stimulated by an increase of erythropoietin secretion (Legenkov & Kozinets, 1996).

Epidemiological data on the incidence of cancer in the population of astronauts are not yet available. For this purpose, an international astronaut/cosmonaut medical database needs to be established, to allow an epidemiological study of the effects of long-term spaceflight on humans. Up to now the accepted increased risk of cancer incidence as a consequence of radiation exposure is given as 3% during the lifespan of an astronaut (see Section 4.2) and that for prolonged exposure to carcinogen contaminants is limited to 0.01% for the lifespan (Coleman & James, 1994).

In addition to body fluid and bone regulation which have been discussed in Section 4.3.2, additional endocrine disorders have been observed during and after spaceflight, such as an elevation of blood thyroxine and of the thyroid stimulating hormone (TSH). Blood glucose has sometimes been found to be elevated during and after flight and blood insulin has been found to be slightly decreased. Blood cortisol, catecholamines and human growth hormone (HGH) have often been found to be elevated during flight and immediately after flight. All these changes probably reflect the stress situation of astronauts and cosmonauts during their spaceflight (Leach-Huntoon et al.,1994; 1998). Protein loss during spaceflight has been well documented and is probably linked with the atrophy of the weight-bearing muscles (see Section 4.3.2). This loss is rather caused by a reduced protein synthesis rate than by a change in the degradation rate of the protein (Stein et al., 1999a). Energy intake has been found to be decreased by 25 % on average during long-term spaceflights (Bourland et al., 2000). Stein et al. (1999b) found an average intake of 24 kcal per kg and day during flight compared to 26 kcal per kg and day before flight (Heer et al., 2000). In addition, low calcium intake, insufficient vitamin D supply or high sodium intake – which is common in microgravity (Heer et al., 2000) – may affect bone density.

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Table 4.12: Probabilities of occurrence of general health challenges during the three mission scenarios

General health challenge	**Scenario 1 180 day Moon mission**		**Scenario 2 1000 day Mars mission**		**Scenario 3 500 day Mars mission**	
	On board the transfer vehicle	On surface of the Moon	On board the transfer vehicle	On Mars Surface	On board the transfer vehicle	On Mars Surface
Intestinal infectious diseases	AR	AR	0.01	0.006	0.007	AR
Non-zoonotic bacterial diseases	AR	AR	AR	AR	AR	AR
Viral diseases	AR	AR	0.01	0.006	0.007	AR
Venereal diseases	AR	AR	0.01	0.006	0.007	AR
Acute respiratory infections	0.35	7.9	39.3	23.0	28.2	1.3
Pneumonia and influenza	AR	0.02	0.1	0.06	0.07	0.003
Bronchitis (asthma included)	AR	0.004	0.02	0.01	0.02	AR
Cystitis	0.08	1.8	8.8	5.2	6.3	0.3
Infections of skin and subcutaneous tissue	0.08	1.8	8.8	5.2	6.3	0.3
Neoplasm (pre and post flight control)	AR	AR	0.008	0.005	AR	AR
Endocrine, nutritional, metabolic, immunity	AR	0.006	0.03	0.02	0.02	AR
Disorder of thyroid gland	AR	AR	0.002	0.001	0.0015	AR
Diabetes Mellitus	AR	AR	0.004	0.0025	0.003	AR
Nutritional deficiencies (avoid by adequate nutrition)	AR	AR	AR	AR	AR	AR
Obesity	AR	AR	AR	AR	AR	AR
Diseases of blood and BFO	AR	0.004	0.02	0.011	0.015	AR
Cardiovascular disease	AR	0.02	0.1	0.06	0.07	0.003
Hypertensive disease	AR	0.002	0.01	0.006	0.007	AR
Ischaemic heart disease	AR	0.008	0.04	0.023	0.03	AR
Haemorrhoids	AR	0.02	0.1	0.06	0.07	0.003
Digestive disease	0.004	0.1	0.5	0.3	0.35	0.02
Appendicitis	AR	0.006	0.03	0.02	0.03	AR
Peptic ulcers	AR	0.002	0.01	0..006	0.007	AR
Abdominal hernia	AR	0.01	0.04	0.02	0.03	AR
Disease of liver & gall bladder	AR	0.01	0.05	0.03	0.035	AR

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Table 4.12 (Continued)

Urinary calculus	AR	0.004	0.02	0.01	0.014	AR
Disease of male genital organs	AR	0.004	0.02	0.01	0.014	AR
Orchitis and epididymitis	AR	0.003	0.01	0.006	0.007	AR
Diseases of breast and female organs	0.004	0.1	0.5	0.3	0.35	0.016
Pregnancy	AR	0.01	0.05	0.03	0.035	AR
Fracture of skull	AR	0.004	0.02	0.01	0.01	AR
Fracture of spine and trunk	AR	0.004	0.02	0.01	0.01	AR
Fracture of upper limb	AR	0.01	0.06	0.04	0.04	0.002
Fracture of lower limb	AR	0.006	0.03	0.02	0.02	AR
Dislocation	AR	0.01	0.05	0.03	0.04	0.002
Sprains and strains	0.006	0.13	0.7	0.4	0.5	0.03
Head injury	AR	0.004	0.02	0.01	0.01	AR
Open wounds	AR	0.02	0.1	0.06	0.07	0.004
Superficial injury	AR	0.02	0.1	0.06	0.07	0.004
Contusion	0.002	0.04	0.2	0.1	0.1	0.007
Crushing injury	AR	0.02	0.1	0.06	0.07	0.003
Foreign bodies	AR	0.02	0.1	0.06	0.07	0.003
Burns	AR	0.02	0.1	0.06	0.07	0.003
Diseases of ear and mastoid process	AR	0.02	0.1	0.06	0.07	0.003
Dental diseases	AR	0.02	0.1	0.06	0.07	0.003
Arthropathies and related disorders	0.002	0.04	0.2	0.1	0.14	0.006
Dorsopathies	0.002	0.04	0.2	0.1	0.14	0.006
Congenital anomalies	AR	AR	0.01	0.006	0.007	AR
Psychoses	AR	0.004	0.02	0.01	0.015	AR
Neurotonic disorders	AR	0.02	0.1	0.06	0.07	0.003
Alcoholic dependence syndrome	AR	0.01	0.05	0.03	0.035	0.002
Poisoning	AR	0.004	0.02	0.01	0.01	AR
Toxic effects	AR	0.01	0.05	0.03	0.04	0.002
Reduced Temperature effects	AR	0.01	0.05	0.03	0.03	0.001
Heat and light effects	AR	0.01	0.07	0.04	0.05	0.002

* AR = Accepted Risk because the probability of occurrence is too low (<0.001)

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The estimated probabilities of occurrence of neoplasms, and endocrine, nutritional and metabolic disorders during the three mission scenarios are summarised in Table 4.12.

Control of cardiovascular diseases other than those which are microgravity-induced

Long-duration missions induce an increase of the incidence and duration of cardiac arrhythmia compared to preflight conditions, probably caused by an adrenergic up-regulation. After long-duration missions, the return to the preflight baseline takes longer (3-4 days) than after a short duration mission (1-2 days) (Yelle, 1998). EVA is also known to induce an increase in the incidence and duration of cardiac arrhythmia, again probably due to a stress-induced adrenergic up-regulation (Charles et al., 1994). The question, whether, and by what mechanisms, spaceflight conditions and EVAs increase the incidence and duration of cardiac arrhythmia, needs further investigation. It is well established that exercise increases the incidence of joint pains (so called "bends") during decompression before EVAs (Powell et al., 1994). Today the denitrogenation protocols used in space are designed to maintain the ratio between the initial nitrogen partial pressure and the final decompression pressure at less than 1.4 ($R<1.4$). No rules are applied concerning the schedule of exercise sessions (necessary during long duration missions) versus the schedule of EVAs (the practice is to avoid any exercise session the day before an EVA is scheduled). Due to the large number of EVAs requested during the planetary surface exploration this aspect will need to be assessed. The estimated probabilities of cardiovascular diseases that are not microgravity-induced, occurring during the three mission scenarios, are summarised in Table 4.12.

During a Moon mission (Scenario 1), resuscitation, health stabilisation, and transportation for a quick return to Earth should be provided in case serious cardiovascular diseases occur. For the Mars missions (Scenarios 2 and 3), resuscitation, health stabilisation, and some therapeutic capability will be essential. Transportation for emergency return to Earth would demand support for health stabilisation over a longer period (probably several months), which might be very difficult to achieve.

Control of digestive disorders

As mentioned above, studies carried out during the NASA-Mir missions have shown a clear energy deficit during flight, with a deficit in protein, due to a reduction in the rate of protein synthesis of as much as 50% relative to the normal rate, rather than to a change in the degradation rate of protein (Stein & Larina, 1998; Stein et al., 1999a; b). The mechanisms responsible for the deficits in energy and protein synthesis are not yet known. As possible causes, poor food quality, altered digestion, altered taste, or in-flight exercise as an indirect effect, are suggested.

It had been hypothesised that mineral and fluid loss during spaceflight were well documented. However, as early as in the Mir 92 mission, Drummer et al. (1993) showed that diuresis and natriuresis are not the cause of body mass decrease during microgravity. Furthermore, in a complete metabolic balance study during the Mir 97 mission, Drummer et al. (2000) demonstrated that sodium might be stored in the organism. Therefore, both, fluid and electrolyte regulation as well as changes in the kidney functions under microgravity are not well understood (Leach-Huntoon, et al., 1998; Drummer et al., 2000). The risk of developing a kidney stone has recently been analysed during the NASA-Mir missions. It appears that the risk of calcium oxalate and brushite stone is increased during flight, with the greatest risk early during flight and immediately after flight. (Whitson et al.,

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1998). The estimated probabilities of digestive and genitourinary disorders occurring during the three mission scenarios are summarised in Table 4.12.

Control of the injuries
There is little evidence available to indicate whether connective tissues repair correctly in space. On the one hand, with superficial abrasions/lacerations no problems occurred during scar formation (Billica et al., 1994); on the other hand, in mammalian connective tissue cultured in microgravity, a depression of cell proliferation has been found (Moore et al., 1996). So far, luckily, no bone fracture has occurred during spaceflight. However, taking into account that bone osteoblasty is depressed during microgravity, consequences are anticipated for the bone repairing process during spaceflight. This is of special concern, because the risk of bone fracture at the levels of the lower limbs and the lower part of the spine is increased by the bone loss induced in microgravity (see Section 4.3.2). The estimated probabilities of injuries occurring during the three mission scenarios are summarised in Table 4.12.

Control of other health challenges
The estimated probabilities of occurrence of other health problems, such as eye, ENT, dental disorders, and musculoskeletal disorders other than microgravity-induced, are also listed in Table 4.12. In these cases, no specific new issues have been identified concerning health control. Table 4.12 also lists the probabilities of mental disease, radiation effects and environmental effects, such as poisoning, toxicity or temperature effects. These three issues are dealt with in detail in Sections 4.2, 4.4 and 5.

4.3.4 Countermeasures against low gravity effects

The countermeasures currently available against orthostatic intolerance, such as sessions using a low body negative pressure (LBNP) device at the end of the spaceflight, fluid and salt loads just before descent, or wearing of the anti-g suit during descent and after flight, with a progressive release of the suit plus appropriate salt and water intake, allow effective control of the post flight orthostatic intolerance caused by transfer from microgravity to the 1g environment (Baldwin, 1999; Baisch et al., 2000). When the countermeasures are used properly, the syncope risk disappears (Bungo et al. 1985; Nicogossian et al., 1994; Charles et al., 1999). These countermeasures should also be effective when coming from microgravity and arriving in 0.16g or 0.38g environments, although this aspect needs confirmation. So far, the only data available are the Apollo missions, and no orthostatic intolerance was reported during the Moon surface exploration.

Current evidence indicates that the countermeasures presently used (LBNP sessions, fluid/salt load before return to gravity and wearing of an anti-g suit during return and the first few days in gravity) have improved the control of the orthostatic intolerance. Without countermeasures the incidence of syncope and presyncope was 33%. Since countermeasures have been used systematically, the incidence of syncope and presyncope is no longer significant, even if cardiovascular deconditioning is still evident. For short-term missions the countermeasures are fluid/salt load before descent, plus wearing of the anti-g suit during return and for the first few hours in gravity. For long-term missions the additional countermeasures are LBNP sessions during the last ten days of the spaceflight, plus wearing of the anti-g suit during return and for the first few days in gravity. The rehabilitation process consists of appropriate salt and fluid intakes, and in the progressive releasing of the anti-g suit under daily stand tests. The duration of this rehabilitation is limited to four days.

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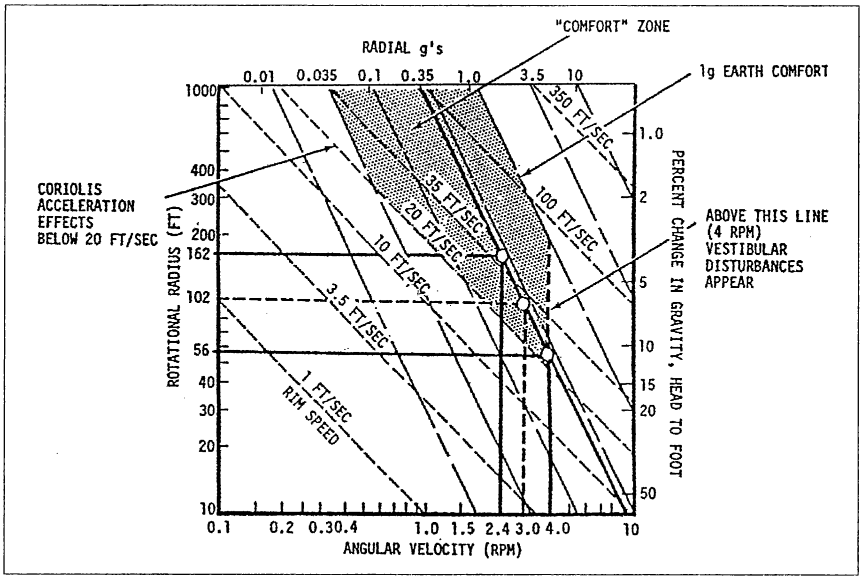

Figure 4.14: Dependence of effects of artificial gravity on rotational radius and angular velocity and narrow comfort zone within a rotating habitat (from NASA, 1971)

Artificial gravity

Artificial gravity has often been considered as a means for preventing microgravity-induced disorders, such as bone loss, cardiovascular orthostatic intolerance, muscle atrophy and exercise capacity impairment, especially during exploratory missions. Two different ways of providing artificial gravity are discussed: (i) permanent exposure to artificial gravity during the transfers and in orbit (Mars mission), or (ii) transient exposure to artificial gravity at specific intervals during the mission. Permanent exposure to artificial gravity was extensively studied by NASA during the 1970s, with the main aim of preventing motion sickness. This sets a maximum angular speed for the rotation of the habitat, which depends on the rotational radius. Figure 4.14 indicates the limits of comfort in a rotating habitat providing artificial gravity. According to these data the comfort zone requires a minimum radius of 17 metres (56 feet) and a maximum angular velocity of 4 rpm, creating an artificial gravity of only 0.35g. Designing a spacecraft with such a capability does not appear realistic at present. Because of the large size required for a comfort zone in artificial gravity and the low level of gravity reached in this zone, permanent exposure to artificial gravity does not seem advisable for exploratory missions at present. It is anyway not clear, whether 0.35g would be sufficient to avoid exercise deconditioning or orthostatic intolerance during spaceflight.

Interest in transient exposure to artificial gravity has reappeared recently, with proposals for self-powered human centrifuge concepts (Krettenberg et al., 1998; Greenleaf et al., 1996). From experiments using a short-arm centrifuge, for subjects deconditioned by head-down tilt, it has been found that a daily run of 1 hour at 2 Gz was beneficial for the orthostatic tolerance, but not for the exercise capacity (Yajima et al., 2000). Another study using a daily run of 30 minutes at 2.4 Gz, with or without exercise in a supine position (up to 90% of the VO_2 peak (five days/week) for three weeks) showed a benefit on exercise capacity for the group

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combining centrifuge runs with supine exercises, while neither group showed any benefits for orthostatic tolerance (group of centrifuge runs alone and group of combined centrifuge runs and supine exercises) (Simonson et al., 2000). A vestibular study performed during and after centrifuge runs on a short-arm centrifuge showed a peak of motion sickness eight minutes after the start of exposure, with some subjects exhibiting milder symptoms during the 24 hours after the runs. A beneficial effect was reported for motion sickness (Young et al., 2000).

So far, using a short-arm centrifuge, a periodic exposure to artificial gravity up to 2.4 Gz has demonstrated a benefit only for orthostatic tolerance, and then not consistently. Possible benefits for microgravity induced amyotrophy and bone loss are still to be demonstrated. The experiments with the centrifuge alone did not show any benefit for maintenance of the exercise capacity. In addition, the experiments showed clearly that discomfort due to motion sickness occurred. Greenleaf et al. (1996) suggest that the astronauts will be able to adapt to this stress and that the side-effects of transitions between different gravitational environments will diminish with repeated exposure. Although one might tolerate bouts of motion sickness associated with Coriolis cross-coupled angular acceleration early in a mission, it would clearly not be acceptable if these symptoms were to re-occur each time the astronaut entered a different gravity environment.

In view of the fact that most of the microgravity-induced orthostatic intolerance can be kept under control with the currently available countermeasures discussed above and assuming that the discomfort of motion sickness induced by daily exposure to different gravity environments would not be acceptable, because it might inhibit the neurosensory adaptation to microgravity, 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) if benefits on exercise capacity have been shown.

4.3.5 Recommended research in health issues

As the human space programmes move towards interplanetary missions, which will include a large number of EVA activities, the physical capacity of the astronauts becomes a major issue for maintaining crew health and operational efficiency. Specific areas of concern include cardiovascular deconditioning, malnutrition, body fluid and sodium regulation, calcium and bone metabolism changes, and muscular changes. Therefore research programmes are recommended which have direct application to health control for interplanetary astronauts. Whereas some of this research can already be performed using short-duration space missions, for example taxi or Shuttle flights to the ISS, satellites, or terrestrial simulation facilities, the major and more important part of these studies requires long-term exposure to the spaceflight environment or comparable simulated conditions. These measures also have the potential to enrich various fields in clinical practice and health prevention on Earth (see Section 7.2).

Research recommended into gravity-related health issues

As mentioned above, the most serious gravity-related health issues pertain mainly to musculoskeletal disorders, neurosensory disorders, and orthostatic intolerance. To control the anticipated musculoskeletal disorders during exploratory missions with up to 1000 days in microgravity (Scenario 2) the following studies are required to identify the mechanisms and causes of these disorders, and to develop suitable countermeasures:

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- Determine the factors influencing the regulation of muscle metabolism during normal activity and exercise, in acute and chronic unloaded states, and during recovery from unloading.
- Determine the endocrine, nutritional and mechanical requirements to minimise degenerative changes in bone, muscle and connective tissue.
- Describe the effects of combined countermeasures (i.e. nutrition and mechanical stress) to maintain muscle mass and bone density
- Determine if the space-induced bone loss is reversible in terms of mass, and ultra- and microstructural organisation.
- Identify bone and muscle metabolism markers (if any) convenient for monitoring the space-induced muscle and bone impairments.
- Develop technologies to determine the threshold in the g-level below which bone demineralisation and muscular disorders occur and to what extent this process might also occur in a 0.16g (Moon) or 0.38g (Mars) environment.
- Determine the factors causing the microgravity-induced back pain.

Concerning the neurosensory disorders observed during transitions between different g-levels, it is still an open question whether, and if so to what extent, long duration spaceflight exposure results in permanent reflex deficits. Therefore, based on present knowledge and experience, the following research requirements for controlling the neurosensory disorders have been identified:

- Determine sensory inputs and co-ordination processes of muscular function before, during and after long-term spaceflight, e.g. using the ISS.
- Determine whether decreases in afferent inputs (vestibular, proprioceptive, somatosensory) that are probably associated with long-term space missions, result in permanent reflex deficits.
- Develop technologies to study whether 0.16g (Moon) or 0.38g (Mars) environments also have an impact on the neurosensory functions.

Applying appropriate countermeasures, orthostatic intolerance can already be efficiently controlled during spaceflight. However, for exploratory missions, gaps of knowledge have to be filled by the following research:

- Determine long-term spaceflight alterations in blood pressure and blood flows, and the functional consequences in tissues and organs.
- Determine whether the extent of cardiovascular adaptation to spaceflight affects the post-flight orthostatic intolerance.
- Develop methods to determine the threshold in the g-level inducing cardiovascular disorders (orthostatic intolerance and exercise capacity impairment), with regard to the reduced gravity levels on the Moon and on Mars

Research recommended into general health issues
In the context of general health issues, emphasis will be given to those phenomena which are considered to be specific for the mission scenarios studied, for example long-term stay in close confinement, or which might be indirectly influenced by spaceflight conditions. Among these, infectious diseases, neoplasm risk, endocrine, malnutrition and metabolic disorders, general cardiovascular diseases, digestive disorders and injuries are of special concern.

The gravity of infectious diseases depends, on the one hand on the capability of the immune system and, on the other hand on the pathogenity of the microorganisms involved. This might have severe consequences for astronauts' health during exploratory missions unless the following research has been performed:

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- determination of the nature, time course, and severity of immune function changes induced by long duration spaceflight, e.g. on the ISS, and identification of which factors are responsible for the changes; a pharmacokinetics study to determine the impact of adaptive responses to long duration spaceflight on absorption efficiency, toxicity, and side effects of antibacterial, antibiotic, antifungal, antiparasitic, and antiviral agents,
- understanding of the mechanisms by which the space environment (microgravity and/or cosmic radiation) influences the genetic stability of microorganisms, and – if this also pertains to pathogenic microorganisms – whether there are therapeutic consequences,

Neoplasm risk, endocrine, nutritional and metabolic disorders are generally considered as an acceptable risk for lunar missions (Scenario 1, Table 4.12), however problems may arise during Mars missions (Scenarios 2 and 3).
Research is also required on the following topics:

- the effects of space-induced endocrine and homeostatic changes and of their consequences on other physiological systems,
- how malnutrition and microgravity during interplanetary missions may affect each other with regard to bone and muscle degradation,
- how adaptive responses to long duration spaceflight affect nutritional requirements and gastrointestinal function,
- how neoplasms common to chronological ageing relate to limitations of cell lifespan and susceptibility to abnormal growth regulation under space conditions, especially with regard to microgravity and cosmic radiation (see also Section 4.2.8).

Studies on the impact on the cardiovascular system of microgravity and other factors, that might occur during exploratory missions, should include the following tasks:

- development of new simulation systems which adequately mimic the effect of microgravity in the cardiovascular field,
- study of the impact of spaceflight on the cardiovascular system, e.g. by increasing cardiac arrhythmia, and identification of the mechanisms,
- investigation into whether EVAs increase cardiac arrhythmia and, if so, identification of the mechanisms,

Concerning digestive and genitourinary disorders, the following have to be determined:
- how adaptive responses to long duration spaceflight affect gastrointestinal functions,
- how adaptive responses to long duration spaceflight (microgravity and cosmic radiation) affect reproductive functions. Are these effects reversible?
- how adaptive responses to long duration spaceflight affect kidney functions (filtration, reabsorption, secretion, excretion) and the consequences in terms of fluid and electrolyte losses and the risk of kidney stones.

Concerning the occurrence of different kinds of injuries, it is important to determine how effectively injured skin, muscle, connective tissue and fractured bone are repaired in the spaceflight environment.

Above all, in order to address the issue of human variability, using modern statistical techniques, it is strongly recommended to construct an international astronaut/cosmonaut medical database, which will allow a

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longitudinal epidemiological study of the effects on humans of long-term spaceflight.

Research recommended into the development of appropriate countermeasures
Effective countermeasures to adverse effects on the human body as a consequence of long-term exposure to microgravity or low gravity are of the utmost importance for securing health and operational efficiency during exploratory missions. Whereas for short-term missions effective countermeasures exist against microgravity effects on human functions substantial research is required in connection with long-term exploratory missions. The following topics have been identified:

- define criteria for designing and operating a countermeasure system (physical exercise, dietary, pharmacological, mechanical) for long duration human exposure to microgravity in order to minimise:

  - musculoskeletal impairments (muscle atrophy, bone demineralisation, back pain);
  - neurosensory disorders and their consequences;
  - flight-induced impairment of exercise capacity;
  - post-flight orthostatic intolerance.

- assess whether periodic exposure to artificial gravity (using a short-arm centrifuge as a potential countermeasure) is acceptable in terms of:

  - neurosensory induced discomfort;
  - reduction of microgravity-induced bone loss;
  - improvement of exercise capacity.

- determine the best exercise/denitrogenation decompression schedule for EVAs.
- design appropriately modified prescriptions (dose, use frequency, ...) for medication used during long duration spaceflight.
- design an optimised dietary regime for long duration spaceflight.
- define the criteria for designing and operating a countermeasure programme for use before, during and after flight, to prevent infectious diseases and dental disorders.
- define and develop a medical and surgical skill maintenance programme using teletraining capabilities.

Research and development recommended in medical engineering
Exploratory missions will require compact autonomous systems for diagnostic and therapeutic purposes. Such onboard medical kits should include instruments necessary to treat the most common dental, eye and ENT diseases. They should be capable of the following diagnostic tasks

- identification of pathogenic microorganisms,
- determination of the *in vitro* Minimum Concentration of Inhibition of antibacterial, antibiotic, antifungal, antiparasitic agents,
- blood cell counting and analysis,
- blood and urine chemical analysis,
- identification of blood or urine biomarkers and quantification of potential endocrine, nutritional, and metabolic disorders, and measurement of the bone and muscle metabolism markers.

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- Measurement of bone ultra- and microstructural organisation, local mechanical bone properties, and bone and muscle metabolism markers (if any), in order to monitor space-induced impairments of bone. For this purpose, a compact abdominal ultrasound, endoscopy and X-ray unit is recommended.

For medical care, the kits should provide the following functions:

- pulmonary life support (with hyperbaric capability) to be used in case of a decompression sickness event, resuscitation or anaesthesia,
- anaesthesia,
- resuscitation,
- endoscopical surgery,
- surgery under microgravity and reduced gravity conditions,
- immobilisation,
- management of adverse effects from low or high temperature, exposure to intense light or radiation.

4.4 Psychological issues

4.4.1 Introduction

Although first reviews of psychological issues in long-duration spaceflight were already published in the early 1970s and 1980s (Connors et al., 1985; Kubis, 1972; Leonov & Lebedev, 1971; *Space Science Board,* 1972), empirical research on these issues is still in its infancy, and only very few "hard" empirical data have been provided during the last decade. One reason for this lack of data is that life sciences research in space and technological developments have largely been dominated by biomedical and life support issues, at least within the western space programmes (*Committee on Advanced Technology for Human Support in Space,* 1997). Within ESA, psychological issues were addressed by the former Long-Term Programme Office (LTPO), which initiated several workshops and also ground-based simulation studies (ISEMSI, EXEMSI, HUBES), but these activities were much reduced after 1997 and cancelled in 1999. Within NASA, psychological issues have been neglected for years in spaceflight research and operations (Santy, 1994). Only recently have they gained more attention, mainly associated with experiences during the American-Russian Mir/Shuttle programme, and been included in strategic considerations for future science in space (*Committee on Space Biology and Medicine*, 1998).

More knowledge has been gained from Russian long-duration spaceflight, different ground-based simulation studies, and research and anecdotal experiences in analogue environments, such as expeditions to Antarctica or long-term submergence in submarines. Even though the validity of different analogue settings and ground-based simulations for generalisation of results to long-duration spaceflight might be questioned, they nevertheless represent the most important source, so far, from which possible psychological issues which might arise during a long-duration interplanetary spaceflight can be extrapolated.

The present analysis is based on the sources mentioned above, as well as on first empirical data and experiences from long-duration orbital spaceflight. Firstly, a review of the current state of knowledge in the area of space psychology is provided and limits of existing knowledge are identified. Secondly, specific psychological issues are identified for each of the different reference scenarios. Thirdly, possible psychological countermeasures are described, and the

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knowledge needed to establish these countermeasures is identified. Finally, based on the first three steps, the research and development needed in order to ensure the success and safety of future interplanetary missions is described.

4.4.2 Psychological issues during long-duration spaceflight

Psychological stressors during long-duration spaceflight

Living and working in a space habitat involves chronic exposure to many different stressors which can degrade the behaviour and performance of astronauts. These stressors can be broadly divided into four different groups:

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

Exposure to these different stressors can be assumed to induce different behavioural stress responses in the individual astronaut or the entire space crew, which can appear in three interdependent effects: (i) impairments of cognitive performance and perceptual-motor skills, (ii) maladaptive individual behavioural reactions, and (iii) disturbances of interpersonal relationships within the space crew and between space crew and ground personnel.

Cognitive and psychomotor performance during long-duration spaceflight

Theoretically, the mental performance of astronauts may suffer from both, direct effects on brain mechanisms by microgravity-induced neurophysiological changes and indirect effects related to stress-induced alterations of the attentional state (Newberg, 1994). The lack of the usual gravitational force in space has been shown to affect different brain mechanisms. Most of these changes are induced by the effects of microgravity on the neurovestibular and motor systems (Reschke et al., 1994b). One particularly important neurophysiological effect in space is the disruption of congruence between vestibular signals and other (e.g., visual, tactile) receptors, as well as between the vestibular otolith and semicircular receptors, caused by the altered signals from the gravity-sensitive otoliths. Another direct effect of microgravity is related to mechanical and proprioceptive changes during the execution of movements, leading to a disruption of the usual relationships between efferent and afferent signals, which has been referred to as a state of sensorimotor discordance (Bock, 1998). Both of these effects can be expected to require complex adaptive processes (for example, a re-weighting of afferent information) and thus, to affect the efficiency of cognitive and perceptual-motor skills that have been established on the ground.

In addition to the specific effects of microgravity on different brain mechanisms, mental performance reduction in space might also be caused by unspecific stress-effects, arising from an impaired attentional state of astronauts, due to the burden of physiological adaptation to microgravity or to the combined effects of other spaceflight-related stressors (e.g., confinement and isolation, elevated CO_2 concentration in the air, or workload). In this case the mediating factor can be assumed to be a stress-related alteration of the pattern of physiological activation (arousal). According to Hockey (1986) such effects do not necessarily lead to

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general impairment of mental performance but can be described more appropriately by a specific profile of effects across different indicators of mental efficiency, including alertness, attentional selectivity, speed and/or accuracy of processing, and working-memory capacity. Considering these indicators, attentional selectivity is one of the most sensitive and might be expected to impair the efficiency of complex performance skills. Generally, attentional selectivity can be defined as compensatory performance adjustment under stress and high workload, which is characterised by focusing the attention on some (high-priority) task-requirements at the expense of other (secondary) elements, in order to reduce the overall attentional demands (Hockey, 1997). It has been found to accompany states of high arousal (e.g., anxiety), as well as of reduced alertness and fatigue. It is assumed that exposure to the conglomerate of stressors in space induces stress states in astronauts, which might appear as mental performance changes reflected in one or more of the different indicator variables described above.

Empirical studies addressing possible effects of spaceflight-related stressors on human cognitive and psychomotor performance have primarily focused on elementary mental functions. Most of them have been conducted during short-term (<30 days) spaceflights. These studies include neuroscience experiments on specific cognitive and psychomotor functions (Leone, 1998; Bock, 1998), as well as human factor approaches to the monitoring of mental performance (Manzey, 2000). In spite of the comparatively small number of studies and the differences in the methodological approach, they have revealed a fairly consistent pattern of effects. Whereas elementary cognitive functions such as memory-search, logical reasoning, mental imagery, and object recognition seem to remain largely unimpaired in space (Leone, 1998), significant disturbances have been found in perceptual-motor and attentional tasks (Manzey & Lorenz, 1998), and the execution of voluntary movements (Bock, 1998). The origin of these effects, i.e. whether they reflect effects of microgravity on the central nervous system or unspecific stress effects, remains unclear. Whereas changes in the execution of voluntary movement are most probably related to direct effects of microgravity, i.e. visual, mechanical, or proprioceptive changes, most of the other effects are more difficult to explain and may also reflect alterations of the attentional state due to side-effects of physiological changes, inadequate work-rest schedules, or sleep disturbances during adaptation to microgravity and the extreme living conditions in the space habitat.

So far, little systematic knowledge is available on the impact of long-duration spaceflight on perceptual, cognitive or psychomotor performance. Only one comprehensive performance monitoring study was conducted during long-term spaceflight, involving one Russian cosmonaut during a 438-day stay onboard Mir (Manzey et al., 1998). The results of this study suggest a remarkable resilience of elementary cognitive and perceptual-motor functions to spaceflight-related stressors, even during an extraordinary long spaceflight. Impairments of performance, alertness and well-being were only found during the first two weeks in space and back on Earth after the mission, i.e. during critical phases of adaptation to changed gravitational forces, which were also associated with a comparatively high workload. After successful adaptation to the space environment, mood and all performance functions assessed returned to their pre-flight baseline levels and remained stable throughout the remaining, more than 400 days in space. Thus, long-term exposure to microgravity and the extreme working and living conditions in space, do not seem, *per se*, to impair the efficiency of elementary performance functions, at least under nominal conditions. Nevertheless, maintenance of operational efficiency and complex skills can become a serious problem during long-duration spaceflight (Sauer et al., 1997). Substantial degradations in the performance of operational tasks

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have been observed during Russian isolation studies and space missions. Most of these seem to be related to unspecific stress effects arising from disturbances of the usual sleep-wake cycle, high workload, or psychosomatic discomfort (Nechaev, 2001). Other degradations of performance can result from cognitive fatigue, an often observed decline of motivation due to low workload, monotony and boredom under prolonged confinement and isolation, or from workload transition, i.e. the need to perform under high workload after prolonged periods of low workload (Gushin et al., 1993; Stuster, 1996).

The current database is clearly too small and includes too few systematic empirical studies to warrant any definite conclusions about the risks arising from mental performance reduction during long-term spaceflight. In particular, the limits of current knowledge are related to three different issues: Firstly, the range of mental performance assessment techniques employed in space research has been severely restricted. A full description and monitoring of the nature of mental performance reduction encountered in space will require the application of integrated test batteries which not only assess the behavioural aspects of information processing (e.g. speed and accuracy of performance), but also include subjective and psycho-physiological aspects, i.e. they provide information about a possible trade-off between performance and associated psycho-physiological costs. Secondly, the origin of the effects (microgravity versus stress) has remained unclear. Thirdly, existing research in space and analogue environments has only addressed a narrow range of mental performance issues. Issues which have not been studied systematically, but are clearly of concern for long-duration spaceflight and future interplanetary missions, include:

- retention of cognitive and perceptual-motor skills over long periods without "on-the-job" training,
- efficiency of perceptual-motor skill learning under conditions of long-term exposure to hypogravity, long-term confinement and isolation,
- impact of extravehicular activities on mental functions and the time-course of recovery,
- impact on mental-functions of transient exposures to artificial gravity.

Maladaptive individual behavioural reactions to long-duration spaceflight
Sleep and fatigue. Sleep disturbances, reduced alertness and fatigue are among the most important factors contributing to reduced well-being and performance reduction during spaceflight and have also frequently been reported from analogue environments (Kubis, 1972; Stuster, 1996). Subjective reports from astronauts, as well as objective studies of sleep during American and Russian space missions, show that sleep in space is often restricted (to 5-6 hours), more disturbed, structurally altered and sometimes also shallower (suppression of delta sleep) than on Earth, with a considerable degree of inter-individual variation (Santy et al., 1988; Gundel et al., 1997; Monk et al., 1998). During Shuttle flights, 50% of crew members on dual-shift flights and 19.4% on single-shift flights reported that they used sleep medications at least once during the flight (Santy et al., 1988), and data published recently show that hypnotics are the second most used medication in orbit (Putcha et al., 1999). Although these observed restrictions and disturbances of sleep may be tolerable for short-term space missions, they might raise the risk of daytime sleepiness and performance impairments during long-duration flights. This is not only suggested by laboratory studies, which show that the adverse effects of restricted sleep on well-being and performance accumulate over successive nights of shortened sleep (Dinges et al., 1997), but also supported by data from Russian spaceflights which indicate a close

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relationship between crew errors and changes in the usual sleep-wake cycle (Nechaev, 2001).

The underlying mechanisms of sleep disturbances and reduced alertness in space are still not known. This holds particularly for the observed changes of sleep architecture and reductions of delta-sleep, which can hardly be explained by environmental factors such as ambient noise, temperature, extended working hours or unsuitable sleeping bags. One reason, which might be assumed to contribute to sleeping problems in space, is a desynchronisation of temperature rhythm and sleep-wake cycles resulting from a 'free run' of rhythms, or a shift of their circadian phase relationships. Such effects have been reported to occur during expeditions to Antarctica and attributed to lacking or, at least, weaker diurnal cues *(zeitgeber)*, normally provided by the regular change of daylight and darkness, and social routines (Gander et al., 1991; Stuster, 1996). The main effects arising from such a desynchronisation include insomnia, daytime sleepiness and performance reduction. Since space and Antarctic habitats during the polar night share the issue of weak (or absent) photic *zeitgeber*, similar effects might be expected to arise during spaceflight. However, only a few studies have addressed this issue (Dijk et al., 2001; Gundel et al., 1997; 2001; Monk et al., 1998). Although a phase-delay of temperature rhythm similar to those reported from polar summer in Antarctica has been observed in some astronauts (Gundel et al., 1997), none of these studies has revealed any indication of a 'free run' of rhythms in astronauts. Thus the strict organisation of diurnal work routines, including a regular schedule of wake-up times and meals, combined with alterations of room illumination in the space habitat seem to represent sufficiently strong external *zeitgeber* to entrain and synchronise the human circadian system to a 24 hour rhythm in space (Monk et al., 1998). However, it does not seem to be sufficient to keep the internal circadian rhythm completely aligned with the sleep-wake schedule or to prevent changes in the waveform of rhythms. Similar to the results reported from Antarctica, phase delays of the temperature rhythm relative to the sleep-wake cycle were found in some astronauts (Gundel et al., 1997), and others showed a reduced circadian amplitude and altered waveform of the body temperature rhythm (Dijk et al., 2001). All of these effects seem to be related to the weakened strength and altered structure of *zeitgeber* in space and may contribute to sleep disturbances, increased fatigue and impairments of well-being during spaceflight. All but one (Gundel et al., 2001) of the studies available so far have, however, been conducted during single-shift orbital spaceflight, with analyses covering only the first 8 to 30 days in space. It remains to be seen whether the results can be generalised to much longer flights and other shift-schedules, and whether the available *zeitgeber* in space are also strong enough to keep the circadian rhythms stable and synchronised even when repeated disturbances or shifts of work-rest schedules occur.

Dysfunctional affective reactions and impairments of mood. Most of the data available about individual psychological reactions to long-term isolation and confinement experienced during space missions are based on anecdotal reports (Stuster, 1996). According to Russian sources, several stages of adaptation to (orbital) long-duration spaceflight can be distinguished (Gushin et al., 1993). The first stage involves basic adjustments to the novel environment and may last two to six weeks (Kanas, 1991). During this phase the astronaut has to adapt to the conditions of microgravity and the accompanying physiological changes, as well as to the other environmental conditions in the space habitat. In addition, the astronaut has to adapt to the new work-rest cycle and the workload according to the flight programme. Impairments of mood and well-being during this phase can be expected to result

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primarily from unpleasant side-effects of physiological changes (headache, space motion sickness) and work overload. The second stage represents a period of successful adaptation where well-being and performance are generally high. The most critical stage, however, begins after the first three to four months in space, when the crew members settle completely into the routine of the mission. The most severe stressors during this stage are monotony and boredom, resulting from low workload, hypo-stimulation and restricted social contacts due to isolation from family and friends. Behavioural reactions to these stressors can include emotional lability and hypersensitivity, increased irritability, and – most important – a considerable decline of vigour and motivation. Without effective treatment (see below) a syndrome, referred to as "asthenia" by Russian psychologists, may develop. This syndrome involves feelings of exhaustion, hypo-activity, low motivation, low appetite and sleep disturbances and can also affect interpersonal relations by withdrawal and territorial behaviour. Other individual behavioural reactions, which have been reported to eventually follow the development of asthenia, include episodic depressive reactions, neurotic developments and the accentuation of negative personality traits (Myasnikov & Zamaletdinov, 1998). All of these individual reactions, which are sometimes considered to be early manifestations of behavioural illness (Kanas, 1998) can be expected to interfere with crew morale and performance and, thus, to seriously jeopardise the success and safety of a long-duration mission. However, only very few systematic studies addressing these dysfunctional reactions during different mission phases have been conducted during real spaceflight or ground-based spaceflight simulations (Kanas et al., 1996; 2000a; 2000b; 2001a), and all of them suffer from a number of methodological constraints which make an interpretation of effects difficult.

More empirical data are available from analogue environments. Based on a review of early results, Rohrer (1961) described a three-stage model of individual reactions to prolonged isolation and confinement, with an increase of anxiety observed during the first stage, depressive reactions to monotony and boredom when the tasks settle into routine and emotional outbursts, aggression and open hostility in the last stage. Bechtel and Berning (1991) assume that, in general, the third quarter of a mission represents the most critical part, independent of its absolute duration, and recent research has provided the first hard empirical data supporting this assumption (Palinkas et al., 2000; Sandal, 2000; 2001). Other results lack consistency regarding both the time-course and the quality of emotional and mood-related effects (Palinkas et al., 1998). This suggests that individual stress responses are largely dependent on the specific characteristics of an analogue, and so it is questionable whether results from any of these settings can be generalised directly to long-duration spaceflight (Suedfeld, 1991; Suedfeld & Steel, 2000). Another issue which has to be better understood before an assessment can be made of the risks arising from dysfunctional emotional reactions and impairments of mood during spaceflight and before effective countermeasures can be developed, concerns the possible moderating effects of individual-related factors on the efficiency of coping with monotony and boredom in isolated and confined environments. Among others, these factors include personal experiences, personality, preferred leisure activities, specific stress-managing strategies, and the kind of social and emotional support available. Even though first studies, addressing some of these issues, have been conducted in different analogues (Palinkas et al., 2000; Palinkas & Browner, 1995; Sandal et al., 1996), current knowledge in this regard is extremely limited.

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Mental and behavioural illness. As defined here, these comprise any abnormal behavioural reaction to the extreme living and working conditions in space that leads to partial or permanent disability of a crew member. Syndromes of this kind include severe neurotic and personality disorders, affective and anxiety disorders (e.g. depression and phobia), and psychoses (e.g. paranoid disorders, schizophrenia) (Santy, 1987). No such illnesses have, so far, been reported from spaceflight. One reason for this is certainly related to the relatively thorough screening process of astronaut candidates, which usually includes some kind of psychiatric evaluation (Santy, 1994). Another reason is assumed to be the very small number of humans who have been into space for more than a few weeks. This does not yet allow for any reliable assessment of incidence rates for different kinds of mental and behavioural illness under these conditions.

Data from analogue environments suggest that the occurrence of mental or behavioural illness resulting from the extreme living conditions in space can indeed become a limiting factor for long-duration spaceflight (Connors et al., 1985; Kanas, 1998). This might, however, not be the same for different kinds of disease. For example, psychoses like schizophrenia have a strong genetic component, which might be detected by inquiries into family background. Furthermore, the first signs of this disease usually appear at a relatively early stage in adolescence. Thus, the disposition to develop this kind of illness can be identified reliably during an appropriate screening process in the astronaut candidate selection stage (Santy, 1987). More significance for long-duration spaceflight must be ascribed to affective and anxiety disorders which might develop as a maladaptive reaction to the extreme working and living conditions in space. This is suggested by experiences from Antarctica and data from prolonged submarine missions, in which anxiety disorders and depression have been among the most frequently observed psychopathological reactions (Connors et al., 1985; Weybrew, 1991).

The few attempts to accurately estimate the risk of developing mental and behavioural illness during long-term spaceflight are based on an international classification of diseases according to ICD-9 (Nelson et al., 1990; RGIT, 1994). Nelson et al. (1990) estimated the risk of different diseases on the basis of incidence rates derived from US Army and Navy personnel, by calculating a medical impact score that took into account the specifics of the spaceflight environment. In their final ranking of possible risks, neurotic disorders, personality disorders and other non-psychotic disorders (ICD-9: 300-316) and non-organic psychoses (ICD-9: 295-299) are among the top ten ICD-sections with highest estimated medical impact for spaceflight. An even more comprehensive approach is represented by the work of RGIT (1994) in which estimated spaceflight incidence rates for different ICD-9 categories have been calculated, based on an impressive database from different analogue environments (military, submarine, Antarctic expeditions, off-shore submarine), and the general population. According to this report the estimated incidence rate for neurotic disorders (ICD-9: 300) during spaceflight is surprisingly low (0.01 cases per man-year), and those for psychoses (ICD-9: 290-296) even smaller (0.002) (see also Chapter 3, Table 3.6). However, the process of collecting data across the variety of environments to derive the final estimations has not been documented very well. Furthermore, these estimations were primarily made for the former Hermes project of ESA and so did not consider space missions as long as interplanetary spaceflight. Looking more specifically at the reported incidence rates from overwinterers in Antarctica, which is considered to represent the currently best available analogue for interplanetary spaceflight, as far as duration and degree of isolation and confinement are concerned, the incidence rates of psychoses are still

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very low (0.00045), but that for neurotic and personality disorders (ICD-9: 300-316) is considerably higher (0.052). Both are higher than for the general population. The latter figure is also confirmed by a recent empirical study of a cohort of 313 military and civilian subjects who spent an austral winter in Antarctica (Palinkas et al., 2001). In this study, an the overall prevalence rate for psychiatric disorders (DSM IV) was 0.052, with mood and adjustment disorders representing the largest diagnostic category (31.6%), followed by sleep-related disorders (21%), substance-related disorders (10.5%), and personality disorders (7.9%).

Another issue, which is of particular concern for long-duration interplanetary spaceflights not offering the opportunity for rescue missions or evacuation, is the human reaction to continuous dependence on automated life-support systems, to high-stress events associated with serious crises like accidents and to environmental disasters or death (including suicides) of crewmates. This not only raises the problem of individual coping with continuous threat and acute fear (see for a review Connors et al., 1985), but also the problem of possible development of posttraumatic disorder, associated with repeated flashbacks, feelings of emotional emptiness, hypo-activity, withdrawal, anxiety, nightmares, sleep disturbances, and depression. This disorder usually occurs with some latency after a traumatic event and can seriously impair both personal and interpersonal functioning.

Interpersonal issues during long-duration spaceflight
Astronaut crews are small groups living close together in a remote and harsh habitat. The success and safety of space missions depend directly on the maintenance of crew cohesiveness, smooth interpersonal interactions and an efficient co-working under these extreme conditions. Any breakdown of communication, co-operation and cohesiveness of a space crew must be considered as an important limiting factor to mission success and safety. This holds in particular for interplanetary spaceflight, with much longer mission durations, with space crews that are larger and more heterogeneous (in terms of cultural and professional background or assigned duties) and with greater autonomy. Situational factors which can be expected to raise interpersonal issues in space include confinement and isolation, which lead to social monotony and boredom by restricting the range of social contacts, and which, irrespective of personal choice, enforce interpersonal interactions with all other crewmates because escape from the presence of others is almost impossible. The possible impact of these stressors on group-processes within small crews has been reviewed in a number of reports, but most of them are only based on anecdotal reports from analogue environments and spaceflight, or early laboratory studies of limited validity (Connors et al., 1985; Harrison & Connors, 1984; Kubis, 1972; Stuster, 1996). However, more systematic knowledge has been gained from a series of ground-based simulations of spaceflight conducted recently under the sponsorship of ESA and the Russian Space Agency (Kanas et al., 1996; Sandal et al., 1995), and even the first results from studies during real spaceflight are available (Kanas et al., 2000a; 2000b; 2001a; 2001b).

Intra-crew issues. Intra-crew issues which have been reported to arise under conditions of prolonged confinement and isolation include, first of all, interpersonal friction and conflicts caused by exaggeration of trivial issues, scapegoating of deviating crew members, territorial behaviour, withdrawal of single crew members and subgroup formation (Kubis, 1972; Sandal et al., 1995; Stuster, 1996).

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These issues can eventually lead to a breakdown of intra-crew communication and crew cohesiveness. An impressive example of this has been reported from a systematical analysis of communication patterns within a six-member crew during the 30-day ESA confinement-study ISEMSI (Sandal et al., 1995). Whereas intra-crew communication at the beginning of the "mission" appeared to be quite normal, with many bilateral interactions among the different crew members, it changed dramatically throughout the course of confinement. At the end, most of the bilateral communications between crewmembers had broken down, almost all communication went through the commander of the crew, and one of the subjects was totally isolated. Even though other results reported in the literature do not always show the same strong effects, episodes of latent or open hostility between crewmembers, and tendencies to form cliques have usually been observed after some time in analogue environments and during spaceflight (Sandal et al., 1995; Stuster, 1996; Stuster et al., 2000). Such developments not only contribute to impairments of individual performance, mood and well-being, but can also affect the efficiency of crew resource management necessary to ensure mission success and safety.

Several factors have been identified as contributing to interpersonal issues under confinement and isolation, the most important include psychological incompatibility of crew members concerning demographic variables, personality characteristics, needs, values and motivation, an insufficiently defined or unbalanced formal and informal role-structure within the crew, formation of cliques, inappropriate leadership behaviour of the commander, and lack of privacy, i.e. the impossibility to withdraw from the presence of others (Nicholas & Penwell, 1995; Palinkas et al., 2000; Stuster, 1996; Suedfeld & Steel, 2000).

In addition, intra-crew issues seem to be affected by temporal factors. According to several sources the most critical time of a mission, in which interpersonal frictions are most likely to arise and crew cohesiveness can decline considerably, include a period after the midpoint ("Third-Quarter Phenomenon") and close to the end of confinement (Kanas et al., 1996; Sandal et al., 1995; Sandal, 2001). However, most of these are based on studies in analogue environments. First studies of the impact of temporal factors on crew interactions during actual spaceflight have not revealed any indications of a similar effect in orbit (Kanas et al., 2001a; 2001b). The currently available database does not however include enough systematic studies to provide a detailed understanding of these different factors and their possible interactions.

Issues of space to ground interaction. Considerable anecdotal evidence from space and analogue environments suggests that increased mission duration and greater autonomy of space crews can also affect the interpersonal relationships and efficiency of co-working between the crew and ground-based monitoring personnel (mission control, principal investigators). In particular two different kinds of effects have been described: (i) open conflicts and hostility between confined crews and outside monitoring personnel (Kanas et al., 1996; Stuster, 1996), and (ii) a progressive reduction of crew-to-ground interactions during actual and simulated long-duration spaceflight, which Russian psychologists attribute to a developing autonomy and "psychological closing" of confined crews, and which not only interferes with professional duties but also make it difficult to monitor the psychological state and interactions of crew members from outside (Gushin et al., 1997).

Given the great importance of efficient co-working and a frank flow of information between the space crew and the ground, any of these effects can become a serious limiting factor in a long-duration mission. First systematic studies of these effects have

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been conducted during actual spaceflight and two Russian simulation studies (Gushin et al., 1997; Kanas et al., 2001a,b). Results from a questionnaire study involving American and Russian cosmonauts, and mission control personnel during Shuttle/Mir missions do indeed provide evidence for disturbed crew-ground relationships (Kanas et al., 2001a,b). Furthermore, they suggest that these disturbances represent displacement effects, i.e. a misdirection or transfer of intra-crew tension and negative emotions to people in mission control, who then are perceived as being hostile, insensitive, and unsupportive. Indications of displacement effects were also found in Russian confinement studies. The results suggest that the most important factors contributing to disturbances of crew to ground interactions include a lack of empathy of ground personnel for the specific situation and living/working conditions of the crew, an increasing egocentrism and sensitivity of confined crews, an increased need of confined crews to get their work appreciated, and a displacement of intra-crew tensions to the outside (Gushin et al., 1997). In contrast, factors which have been identified to foster crew-to-ground interactions include shared experiences of crew members and ground personnel, and the common excitement of spaceflight (Kelly & Kanas, 1993).

Issues of multi-cultural crews. Future exploratory space missions are expected to represent a multi-national collaborative effort and so will require small international crews to live and work together under conditions of isolation and confinement. Consequently, impairments of crew interactions and operations induced by cultural differences and cross-cultural misunderstandings represent another aspect of interpersonal issues which might endanger the success of a long-duration space mission. In a broad sense "culture" is not only limited to the ethnic background of crew members, but also includes aspects of the organisational and professional cultures which have shaped their attitudes, beliefs, habits, and performance styles (Helmreich & Merritt, 1998). Potential risks of multicultural crews include: impairment of crew cohesiveness and co-operation by interpersonal tensions and misunderstandings due to inadequate sensitivity to cultural differences in communication and interpersonal behaviour, which might lead to misinterpretations of behaviour; cultural differences in leadership/ followership behaviour; cultural differences concerning personal space and privacy needs; cultural differences in attitudes towards safety rules and standard operation procedures, and/or subgroup formation along cultural lines.

All of these effects can lead to serious impairments of crew performance, crew morale, and the psychological well-being of individual crew members. However, despite some anecdotal data, only few results from simulated and actual spaceflight or analogue environments are available which could be used to assess the risk for long-duration spaceflight resulting from cross-cultural issues (Santy et al., 1993; Kanas et al., 2000a; 2000b). Moreover, all spaceflight experience with multi-cultural space crews, so far, stems from international Shuttle or Mir missions where cross-cultural aspects were inevitably compounded with "host-guest" differences, i.e. where the missions usually involved one "dominant culture" being the host for crew members from other countries, organisations and professions.

4.4.3 Limiting psychological factors for the three mission scenarios

Future long-duration exploratory space missions to the Moon and Mars can generally be expected to involve the same range of psychological issues and risks as have been reported from long-duration orbital flights, simulation studies and 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. Table 4.13 presents a comparison of some relevant

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Table 4.13: Comparison of factors which are psychologically relevant for different mission scenarios.

Factor	**ISS in LEO**	**Lunar Mission**	**Mars Mission**
Duration (months)	4 – 6	6	16 – 36
Crew size	3 – 6	4	6 (4/2)*
Degree of isolation and social monotony	low to high	high	extremely high
Crew autonomy	low	medium	extremely high
Evacuation in case of emergency	yes	yes	no
Availability of support measures			
ground-based monitoring	yes	yes	very restricted
audio/video transmission	yes	yes	very restricted
e-mail up-/downlink	yes	yes	yes
internet access	yes	yes	no
onboard entertainment	yes	yes	yes
re-supply flights	yes	no	no
visiting crews	yes	no	no
Visual link to Earth	yes	yes	no

** Figures in brackets refer to orbital and surface crew after reaching martian orbit*

psychological aspects of lunar missions, Mars missions, and missions to a space station in low Earth orbit. The currently available database is clearly too small to derive definite risk assessments and further research will be needed in all of the different areas discussed above. In addition, a much more detailed understanding is needed of the concrete scientific and operational demands of space crews and the design of their habitats on exploratory missions, before the psychological issues associated with these missions can finally be assessed and appropriate countermeasures developed. With these limitations in mind, the generalisation of current knowledge to the different reference scenarios is analysed in the following, and key psychological issues are identified, which present specific new challenges in the area of human behaviour and performance and which might raise the psychological risks of these missions beyond that of current orbital spaceflight.

Scenario 1: Lunar outpost on the south pole

The general features of the lunar reference mission are not qualitatively different from those of flights in LEO. This holds for the expected duration of the mission, which is the same as that which the Russians have used for sending permanent crews to Mir, for the crew size, for the availability of space-ground communications and for the possibility of immediate evacuation of crew members in the event of life-threatening emergencies or serious mental or physical illness. Data on flights to the lunar surface already exist from the Apollo programme, even though these earlier missions were limited to short-term flights not involving a permanent lunar base. Consequently it can be assumed that most risks arising from psychological issues do not exceed those which are already known from long-duration orbital flights, and which have generally been accepted when conducting these missions. In addition, most of the currently applied countermeasures to maintain crew performance, psychological well-being, and crew cohesiveness can be used for lunar missions as well, at least in as far as they rely on space-to-ground communication tools, and do not require the availability of regular supply flights. Nevertheless, some specific psychological challenges can be identified, which need to be addressed in order to ensure the operational efficiency and psychological well-being of crews sent to the lunar outpost:

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The permanent sunlight at the lunar south pole represents a possible disturbing factor for the human circadian system and can lead to adverse impacts on sleep quality, daytime alertness and performance. Even though first studies from spaceflight and Antarctica suggest that lack of the natural 24 hour dark/light cycle only has a minor impact on physiological and performance rhythms, given that sufficiently strong non-photic *zeitgeber* are available, the current database is too small to exclude major risks related to this factor.

Due to the small crew size and the lack of visiting crews, social monotony will be higher than in other settings. This will considerably increase the risk of interpersonal tensions, maladaptive affective reactions, impairments of mood, and the development of mental disorders.

The habitat of the lunar base will consist of two small modules (one habitation and one laboratory module), each of them compatible with the payload-constraints of an enhanced Ariane-5 launcher (i.e. a diameter of approximately 4 m and a length of about 15 m). This small size will significantly emphasise privacy issues compared to those known from orbital space stations or habitats in Antarctica. Since lack of privacy is one of the most important stressors under isolation and confinement, this will further increase the risks of interpersonal frictions, maladaptive affective reactions, and impairments of mood.

The lack of supply flights during the 180-day stay at the lunar base will restrict the application of psychological countermeasures which have routinely been used during long-term stays in an orbital station to counter the effects of social monotony and boredom (e.g. sending letters, gifts, preferred food, articles needed for leisure activities). Furthermore, due to the extraordinary kind of experience associated with a lunar mission, psychological issues of re-adaptation to life on Earth can emerge after the mission.

Scenarios 2 and 3: Mars missions

In contrast to the lunar reference scenario, missions to Mars will not be comparable to any other undertaking humans have ever attempted. Even though some aspects of these missions are shared with other settings, (e.g. long-duration stays in orbital space stations, historical expeditions to unknown parts of the Earth, overwintering in Antarctica, long-term submergence in submarines), the total package involving physical and psychological demands given by the long distance of travel, the duration of dependence on 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 to which humans have ever been exposed. The Russian space programme has shown that a stay of up to 438 days in LEO is possible, but this evidence is based on just one cosmonaut who never experienced a period of extreme social monotony that lasted longer than a few months (due to crew exchange and visiting crews), and who received a great deal of ground-based support. During a voyage to Mars and a stay on the martian surface, crew members are expected to endure extraordinarily long periods of extreme confinement and isolation, reaching 500 or even 1000 days. Depending on the constellation of Earth, Mars and Sun, audio-, video-, or data-transmissions between ground and space will be delayed up to 40 minutes, or even entirely blocked. Furthermore, no possibilities exist for any supply or short-term rescue flights. Consequently, ground-based support currently used to foster crew morale, psychological well-being, and mental/behavioural health of crew members during long-duration orbital spaceflight can only be provided to a minimal degree. It must be assumed,

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therefore, that the risks for mission success and safety associated with all kinds of psychological issues known from different isolated and confined environments on Earth, or in LEO, will be much increased on Mars missions. In addition, new psychological challenges will arise during these missions, some of them involving risks for mental and behavioural health which, in principle, cannot be assessed in advance.

The extremely long transfer phase to Mars, in particular, would involve a number of risk factors for the efficiency of skilled performance on Mars where the real mission will begin. These include: (i) the degradation of performance skills which will only be needed on Mars (e.g. related to undocking and landing on the martian surface, operating the life-support systems in the Mars habitats, operating different automatic systems needed for exploration and production on Mars, or operating the experimental equipment, including tele-roboting) because of the lack of "on-the-job" practice possibilities; (ii) the degradation of performance by the need to operate under high workload after a phase of more than 250 days of comparatively low workload. Furthermore, the acquisition of new performance skills during the voyage to Mars can be disturbed by the additional effects of prolonged confinement and isolation. Finally, the lack of the natural 24 hour dark/light cycle during the transfer phase represents a possible disturbing factor for the human circadian system and can lead to adverse impacts on sleep quality, daytime alertness and performance, which can accumulate in the course of the voyage.

Crew members will be required to interact with a large variety of autonomous systems and information devices. Beside regenerative life support systems these can include robots, rovers, tele-operated devices, and – because of the lack of continuous 24 hour ground-monitoring and support known from orbital spaceflight – complex fault-management systems based on intelligent autonomous agents. Interacting with these systems will present a number of new demands which will exceed those known from orbital flight.

Both transfer phases, to and from Mars, will involve long periods of comparatively low workload, monotony of environmental cues, and boredom. In addition, due to the limited size of the interplanetary parent ship, lack-of-privacy issues will be considerably higher than during comparable stays onboard an orbital station. Together these factors will largely increase the risk of maladaptive affective reactions (including asthenia or even manifest syndromes of depression) and disturbances of crew performance and co-operation by interpersonal frictions and conflicts.

Problems of maintaining crew motivation will arise, particularly during the long transfer phase back from Mars, because the real mission (exploration on the martian surface) is finished, but the crew members will still be faced with a long period of inactivity. A decline of motivation during this phase will not only involve an increased risk of performance degradation in nominal and non-nominal operations, but can also have negative consequences for the exercise discipline needed to maintain the physical ability of the crew to live under conditions of Earth gravity after return.

Given the limited size of the crew, the lack of visiting crews, and the very restricted possibilities of two-way space-to-ground communication during parts of the transfer phases and on Mars, social monotony will be much higher than in other known settings. This will increase the risk of interpersonal conflicts and of the breakdown of efficient crew co-operation.

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Due to the very restricted possibilities for psychological (and other) support from ground during the stay in Mars orbit or on the martian surface, and the impossibility of short-term rescue in case of emergencies, crew autonomy will need to be extremely high. This will involve issues related to autonomous management of external crises (e.g. technical failures) and internal crises (e.g. serious physical, mental or behavioural illness), including the need to provide and maintain appropriate technical, medical, and psychological skills, as well as issues arising from the development of group-think within the crew. This phenomenon has been shown to develop in highly autonomous and cohesive crews and is characterised by different symptoms which can seriously impair crew performance and interactions with the ground, such as illusions of invulnerability (i.e. members think they are incapable of making a poor decision), reluctance of crew members to express concerns or disagreement about certain decisions or courses of action, in order to maintain harmony, keeping stereotyped views of people outside the group.

The risk of developing mental and behavioural illness during a mission to Mars is very high (Table 3.6). In particular, the sustained dependence on life-support systems during the Mars mission without any opportunity of short-term rescue, creates an important risk factor for the development of anxiety disorders. In addition, due to the long duration of missions to Mars and the extraordinary kinds of experience associated with such a mission, issues can emerge affecting re-adaptation to life on Earth after the mission.

During the 1000-day Mars mission, specific psychological issues will arise from the split of crew after reaching the martian orbit, with two crew members staying onboard the spaceship orbiting Mars for 525 days and the other four departing for the same duration to the martian surface. In this case two specific issues have to be considered. Firstly, the two orbiting crew members will be exposed to excessive levels of (i) monotony and boredom induced by a low variety of task demands (i.e. tasks limited to monitoring and maintaining the different automated systems of the spaceship), (ii) social monotony induced by the small crew size, which can only partially be balanced by intercom contacts with the crew on the martian surface, and (iii) sensory deprivation (caused by the restricted range of environmental cues during the 1000-day stay in the same spaceship). In combination with feelings of being hurt by not participating in the tasks which are perceived as the real objectives of the mission, these factors will lead to serious issues of maintaining motivation, and will largely increase the risk of developing manifest mental and behavioural illness, including depression, anxiety disorders, and psychoses. This will represent the most serious limiting factor for mission success and safety and contribute to this scenario being by far the most risky one from a psychological point of view.

Secondly, the split of the crew into two sub-crews for about half of the total duration of the mission will lead to a breakdown of crew cohesiveness. Related to this intentionally produced subgroup formation, risks of inter-group conflicts are likely to arise after reunion of the crew (i.e. during the transfer back to Earth), which will amplify the risks of interpersonal issues, degraded crew co-operation and performance that will occur anyway during this mission phase.

Although to a lesser extent than the orbiting crew, the crew departing to Mars will also be exposed to higher levels of monotony and boredom than those known from any other space or Earth-bound settings. It can be expected that these issues will start to adversely affect the psychological well-being and interactions of crew members after the first two to three months on Mars, when the initial excitement of expeditions on the martian surface has decreased, and the tasks to be performed

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have settled into routine. Due to payload constraints the crew habitat on the martian surface can be expected to be much smaller than those used in other isolated and extreme environments (e.g. ISS, Antarctica, submarines). This will considerably increase the significance of privacy issues associated with risks of maladaptive affective reactions, impairments of mood, and interpersonal frictions, all of them jeopardising the efficiency of crew cooperation and performance.

Finally, Mars missions of any duration will involve undeterminable risks related to what might be referred to as an *Earth-out-of-view* phenomenon. Astronauts sent to Mars will be the first human beings who will completely lose the visual link to the home planet. Human responses to this effect are not known and cannot be assessed in advance. Thus they represent a psychological risk of missions to Mars, which, in principle, will be indeterminable and uncontrollable. In any case it can be assumed that the lack of a visual link to Earth will add to the feelings of isolation and autonomy. Beyond that it may induce a state of complete internal decoupling from home. It is conceivable that such a state can involve a broad range of maladaptive responses, including feelings of anxiety and sadness, depressive reactions, or even manifest mental and behavioural illness. In addition, a partial or complete loss of commitment to the usual (Earth-bound) system of values and behavioural norms may result, which, in extreme cases, can involve unforeseeable risks for the performance of mission tasks, individual behaviour, and the interpersonal interactions within the crew, and which might make any external control and guidance of the crew impossible.

4.4.4 Psychological countermeasures

Currently applied psychological countermeasures for long-duration spaceflight
Psychological countermeasures include any actions that might be considered, in order to alleviate the effects of extreme living and working conditions on crew performance and behaviour during long-duration spaceflight, or to reduce the risks related to impairments of mental performance, individual well-being, behavioural health, and interpersonal issues. In principle, two different levels of countermeasure can be distinguished. The first level involves basic issues of environmental engineering (habitability, design of autonomous systems) and work-design, including work-rest scheduling. It represents actions to adapt the living and working environment as far as possible to human needs and capabilities under the extreme conditions of long-duration exploratory missions. The second level involves specific psychological countermeasures which might be applied in order to adapt the astronaut to the living conditions in space, and to provide support during the mission.

Several methods have been developed to try to minimise the risk arising from psychological issues during long-duration orbital spaceflight (Manzey et al., 1995). Even though impairments of performance and psychological well-being of crew members, or the emergence of interpersonal issues, could not be fully avoided by these countermeasures, they have been successful in preventing these issues from becoming a serious danger for mission success and safety. Most commonly applied countermeasures include screening and selection of astronauts, and in-flight support of space crews. In addition, psychological pre-flight training is provided to a limited degree.

Psychiatric and psychological screening and selection of astronauts. Psychiatric screening is used to "select out" candidates who – by established psychiatric standards – appear to be unqualified to become astronauts. Typically, this approach includes psychiatric screening procedures which aim at identifying those few

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candidates among all applicants who suffer from actual mental disorders, or who have had any psychopathological episodes in their biographical or family history which point to an increased risk of developing mental illness.

Psychological selection of astronauts aims at "selecting-in" astronaut candidates who, as far as their basic aptitudes, personality characteristics, attitudes, prior experiences and interpersonal behaviour are concerned, can be expected to meet the specific operational and psychosocial demands of (long-duration) space missions. This kind of selection has usually been applied by Russian, European, and Japanese space agencies (Santy, 1994), but only recently implemented by NASA (Galarza & Holland, 1999a). Assessment tools used for this purpose usually include performance tests, personality questionnaires, analyses of biographical data, and interviews. In addition, short-term isolation chamber tests are used in Russia and Japan. However, only a few of these approaches have so far been validated empirically (Rose et al., 1994). Instead, selection has mainly been based on commonsense considerations, or those that have been found to be valid in other relevant settings (e.g. aviation).

Cosmonaut selection as applied for Russian long-duration spaceflights further includes an assessment of the psychological compatibility of crew members. This assessment is conducted by applying attitude assessments, specific psychophysiological tests, and group exercises. Little has been published about these methods in the accessible literature, and the theoretical basis of at least some of these approaches has been called into question (Santy, 1994).

Psychological training. Pre-flight psychological training has been provided to Russian and American crew members before long-duration spaceflights, but little information has been published about the contents and methods of training. According to Santy (1994), Russian psychological training focuses mainly on stress-management and familiarisation with stressful events during field exercises like survival training, parachute jumping or stays in isolation chambers. American approaches during the Mir/Shuttle programme were limited to theoretical briefings to crew members and their families about psychiatric and psychological issues of long-duration spaceflight. However, with regard to ISS operations, NASA has now also started to complement these activities with behavioural training approaches, including outdoor field exercises in remote areas and training in isolation chambers.

Psychological in-flight monitoring and support. In current long-duration spaceflight, psychological in-flight monitoring and support represent the most important psychological countermeasures. The main objective is to stabilise the emotional state and to ensure optimum well-being of astronauts during a long-duration mission, to maintain the motivation of crew members, to prevent overload of individual crew members, which may lead to exhaustion and performance reduction during the mission, and to maintain a close contact between the space crew and ground. The methods applied for this purpose rely heavily on the availability of effective space-ground communication systems (audio/video transmissions) and of re-supply flights used for sending support items to the crew.

Within the Russian space programme, psychological support groups were introduced with the beginning of long-duration spaceflights on Salyut-6. Monitoring of the emotional state and workload of crew members has been conducted on a regular basis, by analyses of speech from space to ground radio transmissions, evaluation of individual and interpersonal behaviour from video recordings, evaluation of psychophysiological data, and direct communication

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with crewmembers (Kanas, 1991). This allows psychological intervention, if necessary, based on the results of the monitoring. In addition, regular support activities focus primarily on counteracting feelings of monotony, boredom and isolation, and include the provision of entertainment (music, videos), supporting leisure activities, sending private mail and small gifts via visiting re-supply vehicles, providing political and other news from the homeland on a regular basis, private video/audio contacts with family, friends, or popular persons, and private audio-communication with members of the psychological support team (Griegoriev et al., 1985; Kanas, 1991).

NASA started to implement psychological in-flight monitoring and support activities as part of the Mir-Shuttle programme. In-flight monitoring was conducted by evaluation of crew status and support checklists which were completed by the astronauts on a regular basis. In addition, NASA has developed a Spaceflight Cognitive Assessment Tool (WinScat) which is used for repeated self-assessments of different cognitive functions in order to make it possible for astronauts to monitor their mental state. Other psychological in-flight support during the Mir/Shuttle flights resembled the Russian approach.

The current concepts for psychological support of ISS crews are based on those experiences. In addition to the activities described above, this support will include daily up/down link of private e-mails, private psychological conferences between crew members and ground-based support personnel on a bi-weekly basis, and private conferences between crew members and their families on a weekly basis (*International Space Station Program*, 1998).

Concept and elements of psychological countermeasures recommended for exploratory missions

As mentioned above, psychological countermeasures consist of two different levels: (i) basic issues of environmental engineering and (ii) specific psychological measures to facilitate adaptation of the astronauts to the living conditions in space. In the following, essential elements of the recommended countermeasures at both of these levels are reviewed. In general, no differentiation is made between the reference scenarios, because most of the countermeasures apply both to missions to the Moon and to Mars.

Basic countermeasures related to environmental engineering and work design. *(i) Habitat design.* A large number of factors related to the (hardware) design of space habitats can be considered as contributing factors to enhance the psychological comfort of astronauts during long-duration missions (e.g., interior lighting, colour, decor, workstation design). Recommendations for most of these factors have been compiled in the ISS Flight Crew Integration Standards (*International Space Station Program*, 1995) which have been largely adopted by ESA (1994). These recommendations provide first guidelines which can also be used for designing the space habitats for exploratory missions. In the current report some issues are addressed which – considering the identified psychological issues – appear to be of primary concern:

- Personal space and individual crew quarters: Given the increased need for privacy and territorial behaviour under prolonged isolation and confinement, the provision of sufficient personal space and private quarters represents an important psychological countermeasure. There is agreement that personal space needs increase with mission duration, but this requirement may be constrained by technical issues. Clear guidelines are lacking for the minimum

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acceptable habitable volume per person during spaceflight, the most recent studies dating back to the 1960s (Fitts, 2000). In defining such values, cultural differences must be taken into account. These may be considerable (Raybeck, 1991). However, even more important than considerations about the general size of space habitats is the provision of individual quarters for each crew member. Periodic withdrawal from other crewmates represents a healthy coping strategy which should be supported as far as possible by the design of the habitats and transportation system used on the lunar or martian surface and for the Earth-Mars transfer. The size and equipment of the private quarters should support the following functions (in priority order):
- effective visual and acoustic shielding against the outside,
- undisturbed sleep,
- private communication via audio/video transmission and e-mail,
- donning and doffing of personal clothes,
- stowage of personal items,
- individual environmental control (e.g. adjustable lighting and temperature),
- individual work and recreation (availability of a computerised workplace and compact entertainment devices),
- decor which allows for variability and individual preferences (e.g. paintings/pictures presented on screens; adjustable colour of lighting), and
- view outside the habitat.

• Minimum functional size requirements for some of these functions (sleeping facilities, stowage of personal items, donning and doffing) can be found in the NASA and ESA documents referred to above (ESA, 1994; ISS Program, 1995), but need to be reviewed and revised with regard to the specific demands of interplanetary missions and to the technical constraints of Moon and Mars habitats and transportation systems. In addition, functional size requirements still need to be defined for private communication facilities, workstations, and recreation facilities in individual crew quarters.

• Wardroom: In addition to private crew quarters, the design of the habitat should also provide opportunities for meetings and leisure activities of the entire crew. Of particular significance is the provision of space for common meals. Eating together has been found to be an important factor in fostering communication between crew members, and so represents a possible countermeasure to degradation of crew-cohesion (Stuster, 1996). Appropriate recommendations for wardroom design can be found in ISS Program (1995) and ESA (1994).

• Interior decor: Interior decor can contribute to compensating the effects of a decreased range of environmental cues on the Moon and Mars. Even though there is anecdotal evidence that the kind of interior decor (e.g. colour, paintings, pictures) can have an effect on individual well-being under prolonged confinement and isolation, little empirical research has addressed this topic (Stuster, 1996). The most detailed research dates back to a NASA Ames research programme, which has become known as "functional esthetics", and which has provided some recommendations concerning the topics and layouts of paintings and photographs most preferred under conditions of confinement (Clearwater & Coss, 1991). For example, it suggests that, in particular, photographs depicting spacious Earth landscapes might be used to enhance psychological comfort in confined settings. Future research on the preference for specific interior designs and its impact on human behaviour and

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performance should be conducted under conditions of confinement and isolation, in order to develop some more comprehensive design recommendations. With regard to multi-cultural crews, possible cultural differences should be considered.

Basic countermeasures related to environmental engineering and work design: (ii) Design of autonomous (life support) systems. During lunar missions and, even more so, a mission to Mars, the astronauts will be part of complex human-machine systems including automated regenerative life support systems, rovers, robots and other experimental hardware which will demand a rich variety of human-machine interactions. In contrast to orbital spaceflight, systems on Mars will also include interactions with a large number of intelligent software agents, which make operation of the systems possible without continuous 24 hour ground-based monitoring and support. The design of these systems will, to a large extent, determine the quality of life and work during these missions. In order to minimise the workload and stress resulting from interactions with these systems, a strict human-centered design approach should be followed and careful consideration should be given to the distribution of functions between human and machine, as well as to the level of autonomy to be attained (Parasuraman et al., 2000).

One particular issue which must be taken into account with regard to the Mars reference scenarios is the effect of long-term dependence on automated life-support systems without escape possibilities and only very limited on-line ground support in case of equipment failure. Independent of the factual reliability of these systems, this dependence represents a constant threat which can lead to anxiety reactions and – in the worst case – the development of anxiety disorders. In order to reduce the stress resulting from this threat, autonomous life-support systems should not only be designed to optimise automation and to minimise the load of crew members imposed by monotonous repetitive tasks, but they should also provide a maximum level of external on-site controllability and support for trouble-shooting and repair. This is suggested by stress research, which shows that the degree of controllability of a stressor represents one of the most important moderators of the strength of its effect. One promising approach in this regard is to design these systems in accordance with current concepts of adjustable autonomy, which allow for a flexible adjustment of the level of automation, dependent on the situational demands (Dorais et al., 1998). These concepts and their impact on human performance and behaviour need to be explored.

Basic countermeasures related to environmental engineering and work design: (iii) Scheduling of work design and work rest. Three aspects of work-design and work-rest scheduling can serve as effective psychological countermeasures against impairments of individual well-being and performance. Firstly, provision of an appropriate daily load, with tasks which are perceived as meaningful and important, is one of the most effective countermeasures against feelings of boredom and monotony. In particular, long periods of low workload should be avoided, as well as workload transitions, i.e. periods of low workload followed by periods of excessively high workload (Stuster, 1996). This represents a serious issue, especially for the two Mars missions. For the long transfer phase and – in the case of the 1000 day mission – the long stays on the martian surface or in orbit, periods of low operational workload need to be identified in advance. Such periods need to be filled with other meaningful tasks which – dependent on the mission phase – might include academic training, onboard training in important operational tasks, on-site scientific analyses, or writing of publications.

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Secondly, available data suggest that "work rest" scheduling according to a strict 24 hour time regime might provide an effective external *zeitgeber* for the circadian system of astronauts, and be used as a countermeasure to a desynchronisation of circadian rhythms and associated disturbances of sleep, individual well-being and performance. It will be particularly needed in environments where the structure and strength of natural (photic) *zeitgeber* is only weak (lunar south pole, Mars orbit, interplanetary transfer). However, since strict 24 hour work-rest scheduling might not be achievable in all mission phases, it has to be determined to what extent short-term shifts of work-rest schedules affect the circadian system, and whether a recovery from these effects can be achieved after return to a 24 hour work-rest schedule.

Thirdly, instead of providing detailed daily work-programmes to the crew, they should be given sufficient autonomy in planning and scheduling their work within the constraints of a 24 hour time-regime. They should have the autonomy to adapt the scheduling of work tasks to their current workload whenever this is possible. This represents an important lesson learned from early Skylab experiences and Russian missions and it will be a necessity for missions to Mars where ground-space communication is only available to a limited degree and might be blocked entirely for periods of varying duration. However, it is recommended also for Moon missions, in order to foster work-satisfaction and to increase the work-motivation of crew members.

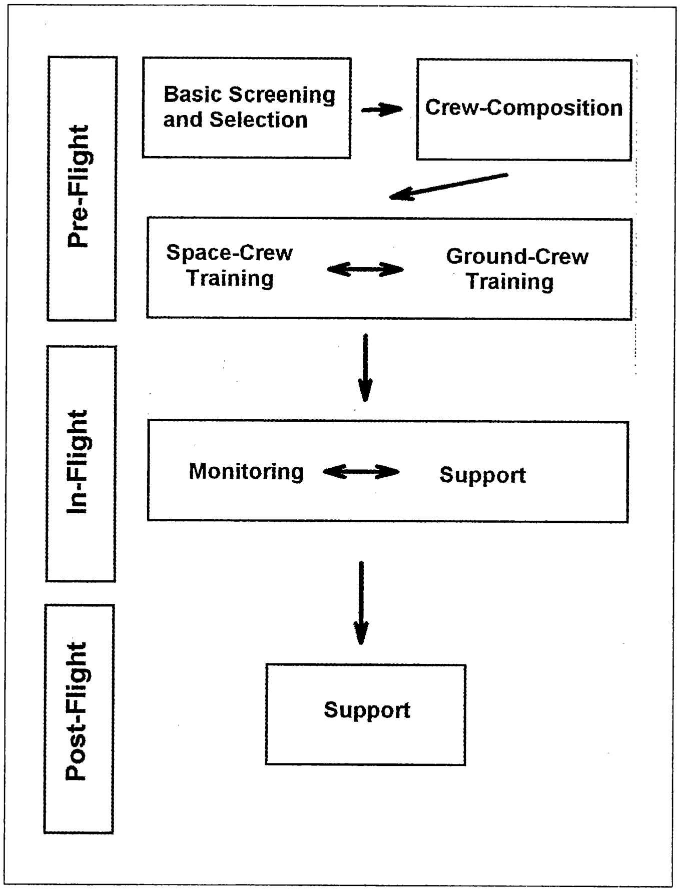

Figure 4.15: Integrated concept of specific psychological countermeasures

Specific psychological countermeasures: General remarks. Basically three kinds of specific psychological countermeasures can be distinguished: (i) selection, (ii) training and (iii) support (Manzey et al., 1995). Whereas selection and training represent countermeasures which can be provided in advance of the mission, support can be provided to individual crew-members or entire crews during and after their mission. Figure 4.15 summarises important elements of an integrated approach, combining different elements of specific psychological countermeasures for the three reference scenarios. During current orbital space missions, most emphasis has been placed on basic selection of astronaut candidates and in-flight monitoring and support. However, given the higher autonomy of space crews staying on the Moon or travelling to Mars – and the limitations of ground support (in particular during Mars missions), the significance of pre-flight countermeasures will increase considerably. Basic screening and selection should be comple-

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mented by a psychologically-guided crew composition, and particular effort should be invested in preparing the space and ground crews for coping with the psychological demands and stress which can be expected to arise during these missions. In contrast, the applicability of current in-flight monitoring and ground-based support will be severely restricted during both Mars reference mission scenarios, and new tools have to be developed and investigated which take these constraints into account.

Specific psychological counter-measures: (i) Basic screening and selection. The first element of psychological counter-measures that can be applied includes a thorough psychiatric and psycho-logical screening and selection of possible candidates for a mission to Moon and Mars. As mentioned above for long-term missions in LEO, psychiatric screening should be applied to "select out" candidates with an increased risk of developing mental illness, and psychological selection should be applied to "select-in" candidates with characteristics that indicate optimum performance and adaptation given the specific demands of the different reference missions. Given the general rule that past behaviour is the best predictor of future behaviour, it is strongly recommended to select only candidates who have already shown successful behaviour and performance in long-term space-flights or analogue environments. This holds at least for Mars missions where any support is limited. Beyond that, a profile of relevant individual characteristics needs to be defined which can serve as a basis for defining psychological selection criteria and for developing assessment tools.

Several systematic attempts have recently been made to identify such characteristics, which and might be used as first guidelines for this approach (Galarza & Holland, 1999b; Suedfeld & Steel, 2000; Stuster, 1996; Ursin et al., 1992). Consistently, they suggest to focus on the following:

- task motivation,
- cognitive and psychomotor performance capabilities,
- personality traits related to performance under stress (e.g., emotional stability),
- personality traits related to interpersonal behaviour (e.g., agreeableness, positive expressivity), and
- interpersonal needs, attitudes and skills.

So far, most of them are only based on anecdotal information or common-sense considerations and the empirical basis of these recommendations is still weak. Longitudinal studies which might empirically relate individual characteristics to actual behaviour and performance during long-duration spaceflight are still missing and it is probably fair to say that it will remain difficult to conduct such studies in the future with a sufficiently large number of subjects, given the relatively small crew-sizes (three to six) and the expected limited duration of ISS missions (not exceeding six months). A more promising approach is to use available databases from analogue environments and to conduct longitudinal research in settings in which a sufficient number of subjects is available (e.g. Antarctica, simulations), in order to determine in more detail and more reliably the relationship between individual characteristics and ability to cope with long-term confinement and isolation (Palinkas et al., 2000; Sandal, 2000; Sandal et al., 1996).

Psychological assessment should not be restricted to an evaluation of behaviour and performance using traditional tools (i.e. performance tests, interviews, analyses of biographical data, personality questionnaires). Emphasis should be put on the

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development and validation of behavioural testing tools (group exercises, isolation chamber tests) which are more suitable for assessing interpersonal skills, and for predicting individual reactions to stress, confinement and isolation.

Specific psychological countermeasures: (ii) Psychologically-guided crew composition. While a psychologically-guided crew composition seems to be unrealistic for near-future ISS missions and most analogue environments, mainly due to political issues or large crew sizes, it must be regarded as mandatory for exploratory space missions, in order to reduce the risks arising from interpersonal tensions and conflicts. The following aspects should be considered:

- Crew size: No empirical data from spaceflight, analogue environments or simulation studies are available to define optimal crew sizes for long-duration missions under conditions of isolation and confinement. Whereas a small crew size can lead to detrimental effects of social monotony, a large crew increases the risk of clique formation, which has been found to impair crew performance (Palinkas et al., 2000). Generally, the crew sizes foreseen for the lunar and Mars mission scenarios are minimum ones which appear to represent the best compromise between operational task demands and cost (see Chapter 2). From a psychological point of view, though, it appears that a larger crew, consisting of six to eight individuals, would be better for crews living on the lunar or martian surface, in order to counter the social monotony. A particular feature of the 1000 day Mars reference mission is the two-person crew which is planned to be left in martian orbit in order to monitor and maintain the technical systems of the orbiter. Beside all other problems associated with this feature (e.g. motivation, sensory deprivation due to environmental monotony, boredom due to restricted range of tasks), it is highly likely that social monotony will lead to severe problems for interpersonal interactions and co-operation, as well as for their individual behavioural health and performance. Early simulation studies by Smith and Haythorn (1972) suggest that dyads fare even worse than triads under conditions of isolation and confinement (i.e. they show higher levels of anxiety and express more complaints), although triads are usually considered to be more difficult with regard to group dynamics. Even though the Mir station usually had a permanent crew of two, the effects of social monotony were effectively countered by the presence of visiting crews and intensive support from ground,. This cannot, therefore, be taken as a positive example for a mission to Mars. Whenever possible, a two person crew should be avoided.

- Age: In principle, crews with similar ages can be expected to interact and perform more efficiently than when the age differences are significant (Morgan & Lassister, 1992). Thus, the composition of a crew with similar ages can be seen as a countermeasure to interpersonal issues. Given the age constraints imposed by radiation issues (i.e. a preference for older crewmembers, in order to reduce genetic risks and long-term effects related to radiation hazards, cf. Section 4.2.7), this recommendation will probably be met, anyway, during long-term missions to Moon and Mars.

- Gender: Gender issues have to be carefully considered in selecting crews for a long-duration exploratory mission. This holds, in particular, for both Mars mission scenarios, because of their extraordinary length and the high levels of confinement, isolation, and crew autonomy involved. No systematic research has ever addressed behaviour and performance issues arising under confinement and isolation in crews with the same and mixed sexes. There is

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virtually no experience with all-female crews and research with mixed-gender crews in spaceflight, simulations, and analogue environments have provided inconsistent results (Stuster, 1996; Suedfeld & Steel, 2000). For example, whereas in the 60-day EXEMSI confinement study, consisting of a crew with one female and three males, the female was credited with having significantly contributed to harmonious crew interactions (Sandal et al., 1995), recent experiences from the Russian SFINCSS study point to possible problems of interpersonal tensions and conflicts in a confined mixed-gender crew. In this isolation study a conflict situation developed due to unwanted sexual advances toward a lone female crew member by one of her seven male crewmates. Experiences with mixed-gender crews in Antarctica also lack consistency (Stuster, 1996). This inconsistency, at least, suggests that mixed-gender crews do not present any general advantage or disadvantage compared to same gender crews. An inevitable gender-related question concerns possible sexual activity during long-term missions, which certainly cannot be excluded, and, even seems likely to occur during the 1000 day Mars reference mission (Suedfeld & Steel, 2000). Even though this issue is not exclusively related to mixed-gender crews, and can be raised for same-gender crews as well (possibly involving homosexual activity or masturbation), heterosexual activity within mixed-gender crews is usually considered to be more conducive to disturbances in intra-crew relations (Connors et al., 1985). Risks commonly associated with sexual activity between crew members during long-duration missions include:

- disturbances of crew-cohesiveness by the formation of couples,
- interpersonal tensions due to jealousy,
- sexual deprivation can be harder to endure in the presence of persons perceived as sexually attractive,
- sexual harassment and violation, and
- unintentional pregnancy.

Only the last of these risks is strictly associated with heterosexual activity, whereas the others can be associated with homosexual activity as well. Furthermore, the first two also occur if strong friendships develop between certain crew members (of the same or different sex) without any sexual content. Specifically in order to address problems of sexual deprivation, it has been proposed to send only successfully married couples on a mission to Mars. However, this option does not appear to be realistic, given the specific profile of professional skills in such crews (see Chapter 2). Despite the fact that this solution might soften moral considerations, it neither presents an effective countermeasure for risks like unintentional pregnancy, nor for disturbances of crew-cohesiveness. The same holds for the suggestion to define a clear code of conduct for a mission (including rules concerning sexual activity). Such rules may easily lose any force, given the high crew autonomy and lack of external control, particularly during a Mars mission. In any case, sending mixed-gender crews with females of reproductive age on a long-duration mission to the Moon and Mars will require effective means of contraception which can be provided to male and/or female crew members and which are suitable for use under the specific conditions of these missions (e.g., concerning pharmacodynamic and pharmacokinetic changes of contraceptive medication in different gravity environments). In addition, crews should include at least two members of the same sex in order to avoid problems of minority (Kanas et al., 2000a; 2000b). Based on currently available data and anecdotal information, and given the inevitable issues and specific risk of pregnancy associated with sexual activity in mixed gender crews, it is clear that sending mixed gender crews to Mars can

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be considered only if the issues mentioned above are dealt with openly, and proper countermeasures are made available to alleviate risks. In future, any discussion on sexual behaviour in space should not be limited to heterosexual behaviour alone. More research on this issue is definitely needed before any final recommendation can be given.

- Cultural background: Crews for exploratory missions to the Moon and Mars will consist of crew members with different professional backgrounds (see Chapter 2), and – since the missions can be expected to represent an international effort – most likely also of crew members with different ethnic and organisational backgrounds. In order to reduce possible risks for co-working, co-living and crew cohesiveness, crews should only be composed of individuals who are as homogeneous as possible under these general circumstances, have experience with other organisational and national cultures and possess sufficient flexibility to adapt to a (new) common crew culture, i.e.

  - are highly fluent in a common language,
  - have worked and lived for a considerable amount of time in the same organisational and national culture, which might become the basis for a common crew culture,
  - have experience of working and living in different organisational and national cultures,
  - have detailed knowledge (based on their own experience) of the 'home' organisational and national cultures of their crewmates,
  - possess a high degree of internal independence of their 'home' culture, and offer a high degree of tolerance towards other professional, organisational, and national cultures.

- Psychological compatibility of individual characteristics: The identification of psychologically compatible crew members will represent a key challenge for all reference missions considered in this report, but is of particular concern for missions to Mars. The concept of psychological compatibility refers to the harmony of individual personalities composing a given crew, with regard to their personality traits, needs, attitudes, and skills. This is a complex concept which is not yet fully understood (Manzey et al., 1995). The currently available research suggests to consider the following factors:

  - homogeneous personality traits (e.g. extraversion, agreeableness, conscientiousness);
  - complementary needs instead of need competition (i.e., crewmembers have differing needs which complement each other; e.g., need for dominance/need for submissiveness);
  - congruent needs (i.e., crew members possess similar needs that can be mutually satisfied; e.g., need for affiliation, need for autonomy, need for achievement);
  - complementary skills (i.e., the skill deficits of individual crew members are compensated for by others);
  - complementary cognitive abilities (i.e., crew members have non-overlapping knowledge which is of interest to the others, such that they can learn from each other and rely on each other for cognitive resources);
  - shared values and norms (i.e., the extent to which crew members share a common value system, belief system and common behavioural norms); and positive emotional attitudes towards each other.

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In particular, constellations of individuals should be avoided whose needs are to some extent competitive or incongruent, and who do not share a common value system. What has consistently been found in empirical studies with confined crews, are negative effects on crew interactions if two or more crew members possess a high need for dominance. This constellation has been shown to cause interpersonal struggles, subgroup formation, and even isolation of single crew members under conditions of confinement (Sandal et al., 1995). In addition, there is also no doubt that common norms (i.e. shared expectations about the behaviour of crew members) and shared value systems within a crew, represent important preconditions for avoiding interpersonal tension and for fostering crew cohesiveness. However, the theoretical and empirical basis for the concept of psychological compatibility of confined crews is still weak and further explorations of the concept are needed. The main body of Western research concerning this topic dates back to the 1960s and 1970s. Most of this research has addressed mono-cultural dyads and triads confined for relatively short periods (a few days to four months), and very little systematic research has been conducted since then. More research might be available from Russian scientists, but little of it is available in the accessible literature.

Another issue which needs to be addressed is the *assessment* of psychological compatibility within small crews. In particular, methods are needed which do not just rely on a comparison of individual profiles of personality traits, attitudes and needs derived from questionnaires, but also include direct assessments of behavioural aspects of compatibility, such as interpersonal interactions in co-operative and competitive tasks, or under stress (Manzey et al., 1995). Such tests have been developed within the Russian space programme, to select crews for Salyut and Mir missions, including a test of psychophysiological compatibility (e.g. Homeostat, Verba-test) (Novikov, 1991). The theoretical concepts underpinning these developments remain questionable, however, and little systematic research has been conducted to validate these approaches empirically (Santy, 1994). In ESA, behavioural assessment tools for assessing interpersonal compatibility were tested for the first time as part of the 60-day EXEMSI study (Manzey et al., 1995). Based on fundamental research on the underlying determinants of interpersonal compatibility these approaches should be explored further.

- Leadership: The leader and his/her style of leadership has been found to be an important factor for maintaining crew morale, motivation and performance during long-duration missions under confinement and isolation. The individual appointed to be the commander of the mission should, therefore, be selected carefully. A comprehensive list of attributes of effective leaders (personality traits and skills) has been provided by Nicholas and Penwell (1995), based on a thorough analysis of empirical research and anecdotal information from different space analogue environments (Table 4.14)

Specific psychological countermeasures: (iii) Psychological training. Psychological training should be provided to space crew members and to selected ground crew personnel in order to prepare both for coping with psychological issues during the mission. In addition, specific training, addressing leadership and the diagnosis and treatment of psychiatric disorders, should be provided to selected crew members.

- Space-crew training: Training of space crew members should focus on strengthening individual as well as crew skills. Individual training should address:

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Table 4.14: Attributes of effective leaders in space analogue environments. (From: Nicholas & Penwell, 1995).

Attributes	Space analogue environments			
	Aviation	Polar stations	Submersibles	Expeditions
A. Personal traits				
Achievement oriented	*	*		*
Personal/professional stake in mission outcome	*		*	*
Confidence, competence, experience		*	*	*
Positive, optimistic outlook	*	*		*
B. Task management				
Solicits subordinates' advice/judgements	*	*		*
Delegates responsibility, then does not interfere	*	*	*	*
Flexible leadership style (takes command in crises)	*	*	*	
Participates with subordinates in routine work		*		*
Emphasises discipline		*		*
Generally democratic leadership style		*		*
Informs subordinates about plans and role	*			*
C. Interpersonal style				
Sensitive to subordinates' personal problems & well-being	*	*		*
Frequent personal contact with subordinates		*	*	*
Openly shows pride in subordinates		*		*
Gives frequent recognition and compliments		*		*
D. Group maintenance style				
Works to reduce clique rivalries and maintain group harmony	*	*		*
Appears non-aligned and impartial in decision-making		*		*
Works to resolve subgroup conflicts		*		*

The stars indicate attributes of leadership which have been found to be important within the different settings

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– interpersonal skills (e.g. communication and conflict management),
– individual self-care strategies and stress-management skills, and
– self-experience and coaching in extreme situations (e.g. survival training).

Group training should be provided to the entire crew in order to establish a high level of crew-cohesiveness, and to provide effective crew skills needed for autonomously coping with conflicts and stress under the constraints of the mission. In order to achieve this, the training should address the following aspects:

– support of a team-building process within the space crew by establishing a stable formal and informal role-structure and a shared system of (behavioural) norms and values;
– diagnosis and management of interpersonal tensions and conflicts;
– "anticipatory problem-solving", i.e. analysing psychological issues which can be foreseen to arise during the mission and developing possible countermeasures, including provision of skills needed for coping with severe internal crises (e.g. serious illness or death of a crew member);
– development of supporting crew skills; and
– preparation of in-flight support activities.

Important elements of such training and the theoretical basis for it have been described in some detail by Manzey et al. (1995). When preparing crews to go to Mars, it will be essential that pre-flight training include a sufficiently long simulation (three to six months) to gain experience with the training, evaluation and coaching of the crew under conditions of confinement.

- Ground crew training: Ground crew members involved in interactions with the space crew during the mission need to be made aware of psychological issues which are likely to arise during the mission. In particular, they should be prepared to cope with 'scapegoating effects', i.e. aggressive reactions and complaints by crew members, which can disturb the communication and co-operation with the space-crew. Also, common team-building exercises with space crew and selected ground crew members might be considered (Kanas et al., 2000a; 2000b).

- Specific training for selected crew members: In addition to training of space crew and ground crew members, specific training should be provided to the commander of the crew in order to enhance leadership skills. Objectives of this training can be derived from the list of attributes characterising efficient leaders, provided in Table 4.14. Further training should address diagnosis and treatment (medication) of psychiatric disorders. This is of particular importance for the Mars mission scenarios, which not only involve an increased risk of such disorders, but also require autonomous treatment without the possibility of evacuating an affected crew member. In order to have a possible backup, this training should be provided to both crew members staying in martian orbit, and to two of the members of the surface crew.

Specific psychological countermeasures: (iv) In-flight monitoring and support of crew behaviour and performance. In-flight monitoring and support should be provided in order to maintain performance skills and to counter the detrimental effects of confinement and isolation on individual well-being, behavioural health, and interpersonal relationships. Important elements include:

- In-flight monitoring: Remote monitoring of crew members' performance and behaviour represents an important basis for early detection of any signs of

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impaired performance and behaviour, and for providing ground-based counselling and advice to the crew (including planning of interventions). Given the different psychological issues which can be expected to arise, this monitoring should address the following areas:

- mental performance,
- circadian rhythm and fatigue,
- emotional state and behavioural health, and
- interpersonal relationships and crew-cohesion.

So far, very few methods are available which could be used for this purpose. During Russian long-term spaceflight, monitoring has usually included analyses of work-rest schedules, crew errors, psychophysiological data, and individual behaviour (including voice) during audio/video transmissions (Kanas, 1991; Nechaev, 2001). Most of these methods have, however, been based only on subjective expert ratings. Recent empirical research on objective methods of voice analysis to detect early signs of emotional stress, based on frequency analyses of audio transmissions, is promising, but has also revealed some severe limitations (Johannes et al., 2000). More research is needed before they can be applied routinely. Other possible approaches which have been recommended and investigated include monitoring of mental performance, based on computerised performance tests (Manzey, 2000) and monitoring of interpersonal behaviour and crew-cohesion based on questionnaires and video-recordings of crew-meetings (Sandal et al., 1995; Sandal, 2001). These methods have so far only been applied for research, and experience from operational applications is missing. The same holds for assessments of fatigue and circadian rhythm. The methods which have so far been used in spaceflight research (e.g. recordings of EEG during sleep, continuous measurement of temperature) are much too complex and invasive to be applied on a regular basis.

For application during long-term exploratory missions, these different approaches must be explored further, and methods need to be developed which take into account the operational constraints of the different mission scenarios. For example, whereas most of the monitoring methods based on audio/video transmissions can be easily implemented for missions to the Moon, they appear more difficult to apply for monitoring crews on Mars, given the communication constraints during these missions. Thus, for Mars missions new approaches must be identified which rely on the primary channels of Mars-ground communication. This might include exploring the characteristics of e-mail communication (e.g. length, content) for reliable and valid indicators of mood and well-being (Gushin et al., 1997).

However, it has to be taken into account that monitoring measures form a very sensitive issue with regard to crew acceptance, and can even contribute to the stress felt (Stuster, 1996). The extent and quality of monitoring must, therefore, be considered very carefully. One possible solution is the provision of self-monitoring methods, which are only used by the crew members themselves, without down-linking of the data. This approach has been pursued in implementing neurocognitive assessment by NASA during the Mir/Shuttle program, and is also foreseen for ISS. However, it presupposes a high trust in crew autonomy, and requires the establishment of decision-aids for the crew members in order to ensure appropriate actions in response to the outcome of such self-assessments. In addition, whereas this approach might be appropriate for monitoring mental performance, effects of fatigue, and specific

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neuropsychological functions after possible traumatic events (e.g. accidents), it does not appear to be suitable with regard to interpersonal relations and crew-cohesion. In this area, self-assessment can be extremely disturbing for the crew and so should be avoided.

- On-board support for maintaining critical skills: Critical (psychomotor) skills which are associated with infrequent tasks (e.g. surgical skills), or which only have to be applied a long time into the mission, need to be maintained. In particular, this will represent an issue for Mars missions where a large number of skills which have been acquired during pre-flight training will be needed only after arriving in Mars orbit or on the surface (e.g. manual landing; tele roboting) and without the possibility of on-line support from the Earth. Efficient on-board training tools must be provided to support skill-retention. In order to develop such tools, it is necessary to identify the level of fidelity needed for efficient on-board skill training and to explore the suitability of new technologies (e.g. virtual reality) for this purpose.

- Sensory stimulation: In order to counter the detrimental effects of the reduced range of environmental cues, additional audio-visual stimulation should be provided. Beside conventional methods, e.g. music, video, or a stimulating interior decor, new technologies such as virtual-environment or virtual-reality should be considered. For crews on Mars, which lack any direct visual link to Earth, the presentation of Earth-bound views and sounds, in particular, may help in maintaining an internal link to the home planet. In order to avoid habituation, new stimuli should be up-linked at regular intervals, provided that technology of sufficient transmission capacity is available. Research should address the effects of such additional sensory simulation under conditions of confinement and isolation, including possible side-effects (e.g. homesickness).

- Recreational opportunities: Individually-tailored recreational activities offer an important countermeasure to boredom and monotony under confinement and isolation. Important elements include (Stuster, 1996):
  - variable exercise equipment for countering behavioural impairments and for release of stress,
  - library of paperback and electronic books (if possible in the native languages of the crew),
  - personal entertainment supplies (e.g. musical instruments, DVD-players, computer games),
  - support for recreational crew activities (e.g. card and board games),
  - support for individual hobbies,
  - support for constructive leisure activities (e.g. formal studies of academic subjects).

  Given the extraordinary length and payload constraints of Mars missions, technical provisions should be made for updating entertainment tools, i.e. up link of new computer games, electronic books, digitised videos, or new music, in accordance with the actual needs of the crew members. Technology and procedures must be developed which offer a large enough transmission capacity to perform such an up-link reliably and in reasonable time.

- News from Earth: Providing news from Earth on a regular basis (preferably in the crew members' native language) will not only provide a countermeasure for boredom and monotony, but can also counter feelings of isolation and internal decoupling from the home planet. News has always been an important

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countermeasure during long-term orbital spaceflight, where audio-video or data-transmission has been used for this purpose. All of these communication links will also be available for Moon and Mars crews (since bi-directional communication is not necessary, and communication delays are tolerable).

Beyond that, more innovative methods for access to news should be considered. A particularly elegant tool in this regard is to provide crew members with access to internet information sources provided by local, national and international newspapers and broadcasting/television stations. This will definitely be an opportunity for crews staying on the Moon. For Mars crews, it might be considered to implement "internet" pages of local and international newspapers and broadcasting companies on an on-board server (linked to individual work stations), and to update these pages at regular intervals. This could even be done under the sponsorship of these companies. However, this approach again pre-supposes that technology is available which provides enough capacity for such an up-link in reasonable time.

- <u>Social contacts</u>: Social monotony has been identified as one of the most severe stressors affecting individual well-being and inter-personal interactions in all of the reference scenarios discussed in this report. Providing social contacts with people outside of the crew will be an important psychological countermeasure. Of particular importance in this regard are regular contacts to family members and friends. Recent research from Antarctica has shown that contacts to family and friends represents an important aspect of social support for contributing to the prevention of depressive reactions, which cannot be provided by fellow crew members (Palinkas et al., 2000). For crews staying on the Moon all conventional communication tools can be used for this purpose and should be offered to the crew, e.g. two-way audio and video communication, amateur radio, and e-mail.

  For crews staying on Mars or in Mars orbit, communication channels for private as well as operational outside communication will be much more limited, mainly consisting of e-mail and one-way audio- and video-transmissions, and even these communication channels will not be available continuously. The advantages and disadvantages of these different tools for Mars-Earth communication and for maintaining social contacts to Earth should be explored in simulation studies which, so far, have usually lacked a simulation of the technical constraints affecting communication during Mars missions.

- <u>Psychological counseling and guidance</u>: Based on in-flight monitoring of crew behaviour and performance, psychological counselling should be provided to the commander or individual crew members, in order to prevent disturbances of performance and behaviour from affecting the mission. For this purpose a psychological support group should be established on Earth, which keeps contact with the crew at regular intervals. For crews staying on the Moon, private psychological conferences based on two-way audio/video communication should be conducted on a regular basis, such as those currently implemented for ISS missions. For crews on a trip to Mars, opportunities for this kind of Earth-based support will be much more limited. In this case, e-mail and one-way audio/video transmissions will represent the only media for this purpose. Simulation studies are needed to explore the possibilities and constraints of these communication tools for purposes of remote counselling and guidance of the crew.

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- Diagnostic tools and medical treatment for psychiatric disorders: Long-duration missions to the Moon, and particularly to Mars, will increase the risk of developing mild or even severe psychiatric disorders (including asthenia). Thus, appropriate diagnostic and therapeutic tools must be provided for such disorders. These tools should include psychoactive drugs for the treatment of psychiatric disorders (e.g. anxiolytics, hypnotics, antidepressants, antimanics, antipsychotics) and also a restraint system for an agitated, psychotic or suicidal crew member which can be used to protect the affected crew member and others from any harm (Santy, 1987).

  With regard to psychoactive medication, more knowledge is needed about how the physiological changes under hypogravity affect the pharmocokinetics of different drugs, which in turn might have consequences for their dosage, route of administration, and possible side effects (Kanas, 1998). In addition, the possible risk of abuse of these drugs must be considered, and rules of access to, and administration of, this medication need to be defined.

- Family-support during the mission: Providing medical and psychological support for crew members' families during the mission can contribute to maintaining the crew members' concentration on the objectives of the mission, by unloading them from considerations about possible problems at home and feelings of responsibility. In addition, families should be coached in interacting with their remote family member and be prepared for possible changes of communication in the course of the mission.

  Specific psychological countermeasures: (v) Post-flight support. Due to the long-term stay in a small group in a confined area, and the extraordinary experience of a mission to the Moon or Mars, problems may arise in re-adjusting to daily life back on Earth, and with re-integration into the family. Further problems may arise from the impact of being famous and the corresponding media attention, which can be expected to put considerable demands on the returning astronauts. Post-flight psychological and psychiatric support should be provided to crew members and their families in order to diminish stress effects associated with these issues, and to assure a constructive coping with the experiences from the mission. All usual methods and techniques of psychological and psychiatric diagnosis, counselling and treatment can be applied for this purpose.

4.4.5 Recommended research into psychological issues

Based on the foregoing analysis, various requirements can be identified for fundamental research and development of countermeasures and these are described below. Table 4.15 presents estimates of their significance in relation to different aspects (fundamental research, technological developments, counter/safety-measures, research in terrestrial analogues, research during precursor flights, criticality for different mission scenarios, European positioning, possible terrestrial applications, and synergies with the 5^{th} framework research programme of the European Union).

Fundamental Research Needs Concerning Cognitive Performance and Perceptual-Motor Skills (Psy01)

- Investigate the impact of hypogravity, confinement and isolation on cognitive and psychomotor performance; identify to what extent impairments of performance in space are related to hypogravity versus non-specific stress effects; include psychophysiological approaches.

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Table 4.15: Best estimates of the identified psychological research and development issues concerning different evaluation criteria

No	R & D Actiivity	Fundamental research	Technology development	Counter-/ Safety measures	Terrestrial Analogue	Precursor Missions (ISS)	Moon Mission Criticality	Mars Mission Criticality	European Positioning	Terrestrial Applicatications	Synergies with EC Programmes
Psy01	**Cognitive and Psychomotor Performance**										
01.1	Effects of hypogravity, confinement and isolation on cognitive and psychomotor performance	***			*** (AE,IC)	***	**	***	**	*	
01.2	Acquisition of new perceptual-motor skills	**	*		** (AE,IC)	***	**	***	*	*	
01.3	Effects of workload transition	**			*** (AE,IC)	**	**	***	*	**	**
01.4	Effects of EVA	**			** (IC, pressurised)	***	**	***	**		
01.5	Effects of artificial gravity	**	**			**	*	**	*		
Psy02	**Maladaptive individual Reactions**										
02.1	Effects of hypogravity, confinement and isolation on sleep quantity and quality	***	*		** (AE, IC)	***	***	***	**	**	**
02.2	Effects of weakened diurnal zeitgebers in space and on Moon on circadian-rhythm	**	*		** (AE, IC)	***	**	** (during transfer only)	**	**	**
02.3	Effects of confinement and isolation on mood and mental/behaviourial health	**			*** (AE, IC)	**	**	***	**	**	*
02.4	Individual characteristics which predict for optimum adjustment	***			*** (AE, IC)	* (difficult due to small sample sizes)	**	***	**	*	
02.5	Long-term dependence on life-support systems	**	*		** (HCC)	*	*	***	*	*	
02.6	Efficacy of individual coping strategies	**			*** (AE, IC)	* (difficult due to small sample sizes)	**	***	**	*	

Codes used for terrestrial analogues:
AE = Analogue Environments (e.g. Antarctica, underwater habitats), IC = Isolation – confinement simulations (e.g. isolation chamber),
HCC = Habitable Closed Chamber equipped with life-support system (incl. altitude chamber, hyperbaric chamber).
Key:
**** High importance, ** medium importance, *little importance.*

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Table 4.15: Best estimates of the identified psychological research and development issues concerning different evaluation criteria (cont.)

No	R & D Actiivity	Fundamental research	Technology development	Counter-/ Safety measures	Terrestrial Analogue	Precursor Missions (ISS)	Moon Mission Criticality	Mars Mission Criticality	European Positioning	Terrestrial Applicatications	Synergies with EC Programmes
Psy03	**Interpersonal Issues**										
03.1	Effects of confinement and isolation on crew interactions	**			*** (AE,IC)	**	**	***	**	**	*
03.2	Interpersonal compatibility and crew composition	***			*** (IC)	*(difficult due to small sample sizes)	**	***	**	**	*
03.3	Effects of confinment and isolation on crew communication with the outside	**			*** (AE,IC)	**	**	***	**	*	
03.4	Individual characteristics which predict for optimum interpersonal behaviour	**			*** (AE,IC)	*(difficult due to small sample sizes)	***	***	**	**	
Psy04	**Psychological Countermeasures**										
04.1	Define functional (size) requirements for individual crew quarters		*	**	*** (IC)	**	**	**	*		
04.2	Investigate interior decor preferences		*	**	*** (AE, IC)	*	*	**	*		
04.3	"Adjustable autonomy" as concept for designing autonomous systems	**	***	***	** (AE, IC)	*	*	***	*	***	**
04.4	Methods for filling low workload periods with meaningful tasks			**	**(AE,IC)	**	**	**	*		
04.5	Methods for maintaining good sleep and stability for circadian-rhythms		*	**	***(AE,IC)	***	***	***	**	**	**
04.6	Development of psychological screening and selection tools		*	***	***(AE,IC)	**	***	***	**	**	*
04.7	Guidelines for psych. crew composition and development of assessment tools		*	***	***(IC)	**(currently not possible)	**	***	*	**	*
04.8	Development of training for space-crew		*	**	***(AE,IC)	**	**	***	**	**	*
04.9	Development of training for ground-crew		*	**	***(AE,IC)	**	**	**	**	*	
04.10	Development of leadership training for commander		*	**	***(AE,IC)	**	**	***	**	**	**
04.11	Development of training for autonomous treatment of psychiatric disorders		*	**	*syst. research not possible due to low incidence rates)		*	***	*	*	
04.12	Development of methods suitable for remote monitoring of crew behaviour and performance		**	***	***(AE,IC)	***	***	***	**	**	*

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- Investigate the efficiency of acquisition of new perceptual-motor skills under prolonged exposure to hypogravity, confinement and isolation.
- Investigate the impact of workload transition (i.e. the need to perform under high workload after prolonged phases of low workload) on cognitive and psychomotor performance.
- Investigate the impact of EVA on cognitive and psychomotor performance and its time-course of recovery.
- Investigate the impact of transient exposure to artificial gravity on cognitive and psychomotor performance.

Fundamental Research Needs Concerning Maladaptive Individual Reactions (Psy02)

- Investigate the characteristics and underlying determinants of altered sleep quantity and sleep-structure in space; conduct studies on the cumulative effects of restricted sleep and reduced sleep depth, and determine its effects on individual well-being and performance.
- Investigate the stability of circadian rhythm under prolonged exposure to a weakened structure of external 24 hour *zeitgeber* (i.e. lack of natural diurnal time cues) under confinement and isolation; address specifically its resistance to short-term shifts of work-rest schedules under these conditions.
- Investigate the effects of long-term exposure to confinement and isolation on mood and mental health and identify the characteristics and time-course of these effects; identify organisational and environmental characteristics which contribute to impaired psychological well-being under prolonged confinement and isolation.
- Identify the individual characteristics (personality, attitude, motivation, needs etc.) which predict for optimum individual adjustment to conditions of confinement and isolation.
- Investigate the behavioural responses to perceived risks associated with long term dependence on life-support systems, and identify critical characteristics of these systems which might contribute to mitigating possible adverse effects.
- Investigate the efficacy of different strategies for coping with physical and social monotony, boredom, and lack of privacy, and identify behavioural and psychophysiological indicators of successful coping.

Fundamental Research Needs Concerning Interpersonal Issues (Psy03)

- Investigate changes in interpersonal interactions and crew structure in confined and isolated crews, including the time-course of these effects, in order to identify the most critical mission phases; identify organisational, and environmental characteristics which contribute to impaired interpersonal interactions under prolonged confinement and isolation.
- Investigate aspects of crew composition as determinants of interpersonal issues under prolonged confinement and isolation; address, in particular, effects related to:
  - personality, attitudes and needs of crew members
  - motivation of crew members
  - gender of crew members
  - cultural differences between crew members.

- Investigate changes of communication with the outside world, in confined and isolated crews, including the time-course of these effects, in order to identify the most critical mission phases; address operational communications as well as communication with family and friends. Identify the individual, organisational and environmental characteristics that contribute to impaired

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outside communication under prolonged confinement and isolation and identify factors which can improve outside communication.
- Identify the individual characteristics (personality, attitude, motivation, needs etc.) which predict for optimum interpersonal behaviour under conditions of confinement and isolation.

Research and Development Needs Concerning Psychological Countermeasures (Psy04)
- Determine the size requirements for individual crew quarters in order to support increased use of these quarters during long-term exploratory missions.
- Investigate interior decor preferences under prolonged confinement and isolation.
- Explore the suitability of "adjustable autonomy" concepts for the design of autonomous systems on the Moon and Mars, and determine their effect on human-machine interactions and performance.
- Identify periods of low workload during interplanetary missions and develop concepts and methods for filling these periods with interesting and useful tasks.
- Identify effective countermeasures for sleep disturbances and instability of circadian rhythm under conditions of weakened external (photic) *zeitgeber* in space and on the Moon.
- Define a profile of individual psychological characteristics that predict for optimum interpersonal behaviour and performance under prolonged confinement and isolation; develop behaviour-oriented methods (e.g. group exercises, role-plays), which can be used to assess these characteristics in addition to conventional questionnaire methods, and initiate research that will allow for longitudinal studies to validate these methods.
- Define guidelines for a psychologically guided crew composition for long-term interplanetary missions to Mars, taking into account gender, cultural background and compatibility of personality characteristics; develop (behaviour-oriented) tools to assess the compatibility of crew-members' personalities, and initiate research to validate these methods.
- Develop psychological training for space crews, in order to initiate a team building process within the crew, to improve individual and crew skills needed for coping with stress and interpersonal conflicts and to establish realistic expectations concerning the working and living conditions during long duration spaceflight; address specifically didactic and experiential training methods which can improve crew-cohesion and interpersonal interactions in mixed-culture crews.
- Develop psychological training for ground crews in order to increase their awareness of the psychological issues of long-duration spaceflight and to prepare for possible changes of crew-ground communication throughout the mission.
- Develop a specific training programme for improving the leadership skills of the commander.
- Develop a specific training programme for preparing crew members for the diagnosis and treatment of psychiatric disorders.
- Develop monitoring measures which can be used for remote monitoring of crew behaviour and performance; specifically address subjective and objective methods suitable for monitoring:
  - cognitive performance,
  - sleep and circadian rhythm,
  - individual well-being and behavioural health,
  - interpersonal relationships within the crew; and
  - explore the suitability of these methods for self-monitoring purposes.

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- Develop "on-board" training tools to support the retention of critical perceptual-motor skills through mission phases where these skills are not needed; identify the level of fidelity needed for such tools; define measures to assess training performance and provide feedback to crew members; consider new technology, such as virtual reality, for this purpose.
- Develop tools to provide additional sensory stimulation on the Moon and Mars; consider, in particular, the provision of Earth-oriented stimuli by new technologies, such as virtual environment and virtual reality; address also possible negative side-effects (e.g. home-sickness).
- Design tools for the support of recreational activities in space; validate the effectiveness of tools currently used during long-duration orbital missions concerning the stabilisation and support of psychological well-being.
- Develop new technologies to increase the capacity for the uplinking of entertainment supplies and news from the Earth to the Moon and Mars, as well as the provision of convenient internet access to crews on the Moon; explore the idea of an electronic "news-and-information" device in the transfer vehicle to Mars, and in the Mars habitat, which can be accessed from individual work stations and supported (updated) from the Earth.
- Develop and test new technologies for crew-to-Earth communication; explore the impact of transmission delays on human communication behaviour, and investigate the suitability of e-mail as the primary (exclusive) source of space to-Earth communication for crews on Mars; address, particularly, its suitability for maintaining social contacts and providing remote psychological counselling and guidance.
- Identify appropriate methods of contraception for use by male or female crew members under conditions of spaceflight; consider the possible effects of hypogravity on the pharmacokinetics of contraceptive medication.
- Develop appropriate restraint systems and diagnostic tools (including computer-based expert systems) and identify a list of psychoactive drugs which can be provided as part of a crew-health facility during missions to the Moon and Mars, in order to allow the autonomous on-board treatment of psychiatric disorders; investigate possible changes of the pharmacokinetics of different classes of drugs under hypogravity and determine the consequences for dosage, route of administration, and possible side-effects.

Several methodological approaches can be considered for the recommended fundamental research and the development of countermeasures. These include research during long-duration orbital spaceflight (ISS), research in appropriate analogue natural environments, such as Antarctica or undersea habitats (in cooperation with the national organisations responsible for these fields), secondary analyses of existing databases from these environments, and ground-based simulation studies in isolation chambers (including altitude and hyperbaric chambers equipped with life-support systems) (Table 4.4.3). This is discussed in more detail in Chapter 7.

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5 Advanced Life Support Systems

5.1 Introduction

Whenever human beings live and work in a confined habitat for extended periods of time, it is the task of the life support system to achieve and maintain a physiologically acceptable environment within this habitat. The environmental control and life support systems (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 this habitat; and (ii) it processes human and other outputs and wastes (Figure 5.1.). The complexity of an ECLSS mainly depends on the size of the crew, the dimensions of the habitat, and the length of stay of the crew inside the habitat. In addition, the method by which resources are re-supplied and the reliability required are important parameters for designing an ECLSS.

The first experience in ECLSS was gained at the beginning of this century, with submarines. Today, nuclear submarines are equipped with ECLSS capable, in submerged state, of supporting crews of more than a hundred for several weeks. In the last decades, experience has been gained in ECLSS on board Earth-orbiting stations, such as the Russian space station Mir, the International Space Station ISS and their respective transportation vehicles, the US Space Shuttle and the Russian Soyuz capsule. The ECLSS on board the ISS allows a permanent crew consisting

Functions of Life Support System

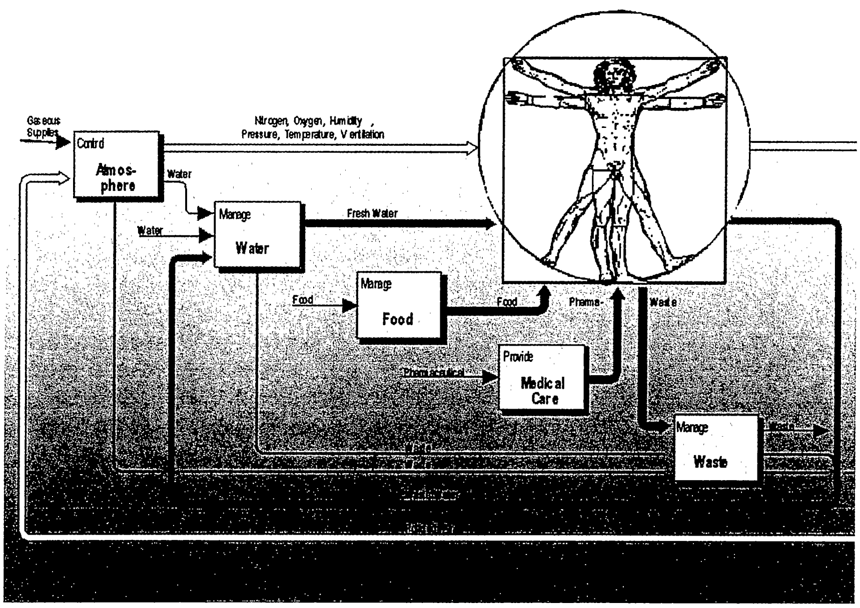

Figure 5.1: Generic functions of an ECLSS relating to the atmosphere, water, food, medical care and waste produced.

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of at least seven members to live and work for a very long time. The concept applied for these space stations implies, on the one hand, the possibility of evacuating the crew back to the Earth within a relatively short time and, on the other hand, the possibility of re-supply of consumables without limiting budgetary constraints, and, even more importantly, without technical/physical constraints.

The requirements placed on an ECLSS change drastically when humans are faced with exploratory missions involving interplanetary and planetary environments. Whereas, so far, the ECLS techniques available are based almost entirely on physico-chemical processes, exploratory missions require alternative ECLSS, including (i) biological/ bioregenerative processes mimicking natural processes of our biosphere on Earth; and (ii) the use, for as many purposes as possible, of natural resources available on extraterrestrial bodies. Different ECLS issues have to be considered for the transfer phases from the Earth to the Moon or to Mars, respectively, and back, and for the stay on the surface. On a mission to Mars, the main difference between transit and the stay on the surface is the additional space and energy available on the surface, due to the installation of additional habitat(s) (e.g. inflatable structures, local resources) and (eventually nuclear) power plants, which may be brought to Mars before the arrival of the crew (NASA, 1997 and 1998).

The purpose of this chapter is to summarise present technologies available for ECLSS and to recommend research and development for advanced life support technologies for exploratory missions to Mars and the Moon, as defined by the three reference scenarios (see Chapter 2). The recommendations are based on the requirements defined in Tables 3.3 to 3.5.

5.2 Physico-chemical life support systems

5.2.1 Available physico-chemical life support technologies (Eckart, 1994)

The life support technologies so far implemented in the ECLSS of the two major manned space stations in LEO, the Russian space station Mir and the international space station ISS, integrate physico-chemical technologies to meet the life support functions (Table 5.1). Common to both systems is that food and nitrogen are totally supplied from the Earth, that oxygen is supplied from the Earth (in various forms, e.g. bound in water), that solid waste is returned to the Earth or burnt during re-entry, and that water is recycled to a large extent. Hence, they are partially based on regenerative techniques, in order to reduce the necessary upload-mass-related operational costs. Essential functions are covered by redundant systems or backups. However, the safety and maintenance concepts rely heavily on regular re-supply flights (even for recycling systems) and they benefit from the short distance of LEO to the Earth's surface, allowing rapid evacuation of the crew in the event of severe problems.

European activities in ECLSS development were initiated together with Europe's moves towards autonomy in space (Columbus/Hermes) (ICES, 2000). The spectrum covered human transportation to and from space, the stay in orbit in a free-flying element, and EVAs.

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Table 5.1: ECLSS techniques available and currently applied in the space stations in LEO.

Component	Non-regenerative ECLSS	Regenerative ECLSS
Air	O_2/N_2 stored/re-supplied from Earth CO_2 control by consumables (e.g. LiOH)	Oxygen reclamation by means of – CO_2 concentration (solid adsorber, molecular sieve technologies, SOFC), – CO_2 reduction (most likely by Sabatier process) – O_2 generation by electrolysis
	Contamination control by consumables (e.g. activated charcoal)	Contamination control by catalytic processes
Water	Stored/re-supplied from Earth	Reclamation of waste water by – osmosis and reverse osmosis processes, – membrane technologies, – distillation processes, – ultrafiltration and catalytic processes.
Waste, solid	Stored/conditioned and returned to Earth, or disposed of in space	Processing of solid waste by – compacting and drying
Food	Stored/re-supplied from Earth (e.g. dry, frozen food, cans)	Limited production of special diet only

5.2.2 Planned physico-chemical life support technologies for LEO and exploratory missions

In order to achieve lower operational costs, several improvements are planned of the ECLSS on board the ISS (Table 5.1). They include a Sabatier Reactor, which allows conversion of the CO_2 in the air into water and methane and by this means reduces the required water upload for oxygen generation (Zubrin et al., 1994). In this way, the annual upload of water, required for a crew of seven on the ISS, would be reduced from 1475 kg to 396 kg. If the methane cannot be used as propulsion for attitude control, a further improvement of the mass balance (no hydrogen loss) can be achieved by pyrolysis of methane, producing carbon and hydrogen, the latter being fed back into the Sabatier process. Including pyrolysis into the system would further reduce the annual water upload by 74 kg to 322 kg.

In addition to the development of new systems improving the mass balance on the ISS, further emphasis is given to increasing the reliability of the existing life support systems on the ISS, and on reducing the maintenance effort for the equipment already installed.

For the Crew Rescue Vehicle (CRV) of the ISS no new ECLSS technologies are planned. However it might become necessary to implement new technologies to ensure correct functioning after long-term docking in orbit. The estimated development status, for the space-faring nations, of physico-chemical ECLSS for space applications is shown in Table 5.2.

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Table 5.2: Status of knowledge in physico-chemical ECLSS developments for space applications.

	Recycling of			
	Air	**Water**	**Waste**	**Food**
USA	mature	mature	medium	low
Europe	mature	low	low	none
Russia	mature	mature	medium	none
Japan	medium	low	low	none
China	low	low	low	none

For ECLSS developments for exploratory missions to the Moon or to Mars, as defined in the three reference scenarios, the technical requirements differ substantially from those for the ISS: (i) on the surface of these bodies, the gravity, although lower than on Earth, allows the use of less sophisticated equipment than required for ISS applications, where everything has to work under microgravity conditions; (ii) on the other hand, because of the large distance to the Earth, the reliability, unattended operation and robustness requirements of ECLSS for Moon/Mars applications are higher than those for the ISS.

So far, no information is available from Russia on ECLSS technology developments for Mars missions. In the USA, breadboarding of small flight experiments is currently under way, aiming at the use of Mars' on-site resources. Published work refers to:

- accumulation of martian CO_2 by absorbers and thermal heating for pressurisation, to avoid mechanical compressors (Sridhar, Vaninam, 1997);
- production of oxygen by solid oxide electrolysis of martian CO_2 (Sridhar, Miller, 1994);
- propellant production with a down-scaled in-situ resource utilisation (ISRU) demonstrator unit planned to be transported to Mars during a precursor flight (Zubrin et al., 1994).

ISRU and *in-situ* propellant production (ISPP) will certainly form an essential part of any ECLSS on the Moon or on Mars. However, these systems will be designed completely differently for the two applications. Whereas the atmosphere and its constituents represent the main ISRU/ISPP source on Mars, the lunar soil and regolith will be the main ISRU/ISPP source on the Moon. Since every ISRU/ISPP design has a strong impact on every potential ECLSS realisation, it is also very likely that ECLSS configurations for application on the Moon will be very different from those suitable for Mars.

5.2.3 Recommended developments for advanced physico-chemical life support

The level of knowledge available in Europe concerning atmospheric conditioning for space applications is quite mature. Physico-chemical techniques include ventilation and air conditioning systems (temperature and humidity control, pressure control), air revitalisation systems (CO_2-control, CO_2-reduction, and O_2-reclamation, gaseous contamination control) including all relevant measurement/sensor techniques and controls. Other technologies, in particular those concerning water treatment and

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Table 5.3: Status of physico-chemical life support technologies developed in Europe

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 heat exchanger	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 included
O_2-Generation	Fixed Alkaline Electrolyte (FAE)	advanced breadboard, flight experiment planned
Methane cracking	high temperature pyrolysis	initial breadboard tests
Contaminants control	catalytic oxidisers	initial breadboarding
	regenerative charcoal- type absorbers	feasibility checks
Toilet	compaction, liquid separator	stopped with HERMES
Water management	conditioning, storing, distribution	stopped with HERMES
	liquid/ gas separators	breadboarding with membrane
O_2-reclamation	integrated/modularised system of solid amine, Sabatier and FAE	closed chamber tests, 3 to 7 person load
Waste management	collection, compacting, conditioning, storing, processing	stopped with HERMES

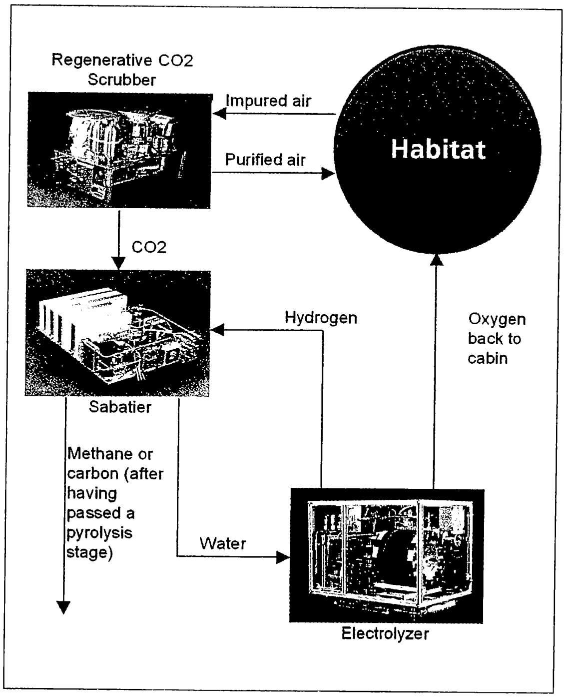

Figure 5.2: Air revitalisation system demonstrator

waste treatment have been investigated in the frame of previously planned space projects, most of which were cancelled in the last decade. Table 5.3 lists the most important results from the broad range of technologies addressed.

Based on this broad experience in ECLSS for human spaceflight, as shown in Table 5.3, it is recommended that cabin air management should be the prime focus in the further development of ECLS technologies in Europe, but extended by activities for water and waste management. In this context, the air revitalisation system demonstrator (Figure 5.2), consisting of a regenerative CO_2 scrubber attached to a Sabatier reactor, is suggested as a promising process for winning back O_2 into 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.

Physico-chemical life support technologies will remain the backbone of any ECLSS for

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LEO and Mars or Moon missions, but bioregenerative techniques will be integrated, especially for food and waste management (see Section 5.3). As already stated, the use of local resources will strongly affect the ECLSS of future missions. This is obvious for Mars, where CO_2 or water found locally may be used for oxygen generation for the crew and for the generation of propellant for return vehicles (see Section 5.5). The European technologies listed in Table 5.3 can be considered as a solid base to be adapted for such applications.

Another important step towards the development of an advanced life support system for exploratory missions is the development of an internal resource management system. An electrolyser could, for instance, provide the fuel for a fuel cell as well as acting as part of a regenerative power system. Such an integrated approach, which is recommended for ECLSS for lunar missions and, in particular, a mission to Mars, requires that attention be paid to psychological issues early in the mission planning. The astronauts will be part of complex human-machine systems, including automated regenerative life-support systems, which will impose a rich variety of human-machine interactions. The design of these systems will to a large extent determine the quality of life and work during these missions. In order to minimise the workload and stress resulting from interactions with these systems, a strict human-centred design approach should be followed, and careful consideration should be given to the distribution of functions between humans and the machine, as well as to the level of autonomy to be attained (see Section 4.4.4). On the surface of the Moon, and especially on Mars, autonomous ECLSS should also offer a maximum of external on-site controllability and support for trouble-shooting and repair. Such human-machine interactions should be further explored in the future when designing an ECLSS for exploratory missions.

Besides the technical aspects, some programmatic issues are also worth considering. In the past Europe has tried, but not succeeded, to establish a sound economic base, within its programmes, for life-support technology. The number of experienced companies that are willing and able to engage in space programmes, with their lengthy development steps and small production quantities, is rather limited. Present European advanced physico-chemical life support technology provides a solid base for future missions, in LEO and beyond, as defined in the three mission scenarios. However, care should be taken to further foster these capabilities, which are also required for European industry to be competitive.

5.3 Biological life support systems

5.3.1 Components for the biological regeneration of a human habitat

A biological life support system (BLSS) is usually considered as complementary to a physico-chemical life support system, able to support certain functions of a life support system, in order to maintain or improve the habitability for the crew. The three main biological components so far considered for a human life support ecosystem are, microorganisms, algae, and higher plants and, to a lesser extent, yeast/fungi and animals. The characteristics of these biological components with regard to their advantages, disadvantages and constraints in bioregenerative processes are shown in Table 5.4. When choosing a biological life support system and defining its design, it is important to note that, in contrast to most physico-chemical processes, biological subsystems usually support more than one function (e.g., plants or algae are capable of both regenerating water and the atmosphere and also of producing food, whereas Sabatier or Bosch processes are suited for

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CO_2 reduction only and they can be coupled to electrolysis for O_2 generation, i.e. atmosphere regeneration). In many instances, the use of one kind of biological component imposes the use of another (e.g. plants need nitrate which can be produced from ammonia by nitrifying bacteria with ammonia coming from the degradation of urea). A biological life support system needs to include at least one autotrophic (mainly phototrophic) organism, such as algae or plants, to build up the biomass.

Algae and cyanobacteria

In our biosphere, algae play a significant role in the photosynthetic restoration of organic substances. The annual production of organic substances due to algae (mainly unicellular) is 5.5 x 10^{10} tons, which amounts to 33,5 % of all organic substances synthesised in the biosphere (1.64 x 10^{11} tons) (Woodwell, 1970). For use in a biological life support system, the most attractive candidates are the various species of green unicellular algae or cyanobacteria, due to their consummate autotrophism, their simple and asexual method of reproduction and their broad ecological plasticity (Gitelson & Mac Elroy, 1999). As early as the 1960s, various unicellular algae species and strains were cultivated under artificial conditions, as the core, or as elements, of a closed life support system (see also Table 5.8). With a *Chlorella*/Mouse system, Eley & Myers (1964) were the first who attempted to create such a closed system.

Chlorella are the most studied algae for a biological life support system (BLSS) and this organism was extensively studied by Russian scientists (Gitelson & Mac Elroy, 1999). Other species were also studied, such as the unicellular green algae *Scenedesmus* and *Chlamidomonas*, and the cyanobacteria *Anabaena*, *Anacycstic* and *Microcystis*. One of the main drawbacks of these algae and cyanobacteria is their inedibility (low digestibility, high nucleic acid content), which prevents their use as a food source, although the biochemical composition of *Chlorella*, for example, demonstrate that they contain all essential amino acids, vitamins and lipids (but insufficient carbohydrates) for human needs. A more promising organism, with regard to its acceptability as food, is the cyanobacterium *Spirulina* (Dillon & Phan, 1993; Tranquille & Emeis, 1992), which can be used as the core photoautotrophic organism in a BLSS (Mergeay et al., 1988).

Cooke (1971) raised several points of criticism on the suitability of monocultures of unicellular organisms, either photosynthesising or chemosynthesising ones, in controlling biological regenerative systems. These include (i) that their control is complicated and energy consuming; (ii) that the system could degenerate genetically; and most importantly (iii) that its biochemical composition does not conform to human requirements in terms of the O_2/CO_2 ratio (e.g. the GEC differs from unity) and in term of biomass composition in case it is proposed for food. These pessimistic conclusions were probably one of the reasons why further studies in the USA were focused on higher plants as the core element for the biological regenerative systems.

However, later experiments have shown the suitability of algae to maintain certain functions in a BLSS (Gitelson & Mac Elroy, 1999): (i) experiments BIOS 1, 2 and 3 have demonstrated the efficiency of algae (*Chlorella*) as an element for gas regeneration, water treatment and food production; (ii) the strain *Chlorella* remained genetically stable during 30 years of experimentation in Russia; (iii) simple and reliable automated control systems can be used for photobioreactors (Demey et al., 2000); (iv) a GEC of 1 is achievable on the basis of steady controllable growth of algae on a balanced nutrient medium. Smernoff et al.

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Table 5.4: Suitability of different biological systems for bioregenerative processes

Biological component	Advantages	Disadvantages	Specific constraints
Algae	Convert CO_2 to O_2. Some biomass can be a fresh food complement (vitamins, minerals, amino-acids). Reduced volumes and area. Controlled processes. Low inertia (rapid dynamic response) Easily understood and controlled	Participation of the biomass in food is limited (variable with species; depends on the nucleic acid content) Low carbohydrate and fat content	Use of photobioreactor. Light (Sun or artificial) must be managed, to control O_2 production. Nutrient medium must be controlled to achieve a Gas Exchange Coefficient (GEC) = 1. In space, requires a solution to gas/liquid mass transfer problems
Higher plants	Convert CO_2 to O_2 Varied source for food (large crop possible). Perspiration is a very efficient water treatment system. Psychological aspect	About half of the biomass produced is inedible (waste). Inedible material (fibre, lignocellulosic material) is difficult to degrade. Carbohydrate source, but low essential fat and protein content. Crop area increases quickly with the number of crops. High manpower required. (seeding, planting, crop cycles). High inertia and low dynamic resonse time: system difficult to control.	Use of closed growth chamber (specific to crop and growth cycles....) Sexual reproduction can be problematic for non-self-pollinator species Nutrient solution must be controlled.
Microbial organisms	Often simple controllable processes are involved. Chemoheterotrophic and chemoorganotrophic organisms are able to achieve organic waste degradation (water treatment, gas contaminant filter...). Usually low inertia (rapid dynamic response). Usually low volumes and area. Low energy cost.	Biomass in principle not consumable (high nucleic acid content). The biocenosis required for some processes is more difficult to manage (sewage treatment...). By-products can be undesirable (methane, CO_2, H_2......). Microbial contamination risks.	Use of bioreactors. Risks of microbial contamination of other subsystems must be considered in the design and integration of bioreactors. It is better to work with known species.
Yeast/Fungi	Contain enzymes for the degration of fibres (eventually lignin). Can be part of the diet. Low energy cost.	Technologies for integration as autonomous subsystems are not clearly identified. Complex metabolism. Probably difficult to control (like higher plants).	Technologies not clearly identified.
Animals	Source of proteins and essential fats. Part of the "classical" human diet.	Complicate the system in terms of exchange fluxes, dimensions, hygiene safety (contaminant) Preparation of food (killing animal, butchery...) presents technical (safety) and psychological problems	Subsystem depends on the kind of animal used. The simplest are aquatic systems supporting small fish and molluscs.

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(1987), proposed cultures on two nitrogen sources (nitrate and urea) to obtain an autotrophic quotient (AQ) or photosynthetic quotient (PQ) compatible with the respiratory quotient (RQ) of the crew; and finally (v) cyanobacteria such as *Spirulina* can be used as a food complement.

Further advantages of unicellular algae are their rapid dynamic response, which makes them one of the best biological alternatives to physico-chemical systems for gas O_2/CO_2 regeneration. The short life cycle of about two days is an advantage for safety and reliability of the system, as an algae culture can be quickly restarted after a failure or a shutdown (for example, in case of contamination of the culture or failure of the control system). Their contribution to other functions of a BLSS, such as food production or water recycling/regeneration, may also allow them to be considered as a valuable core element in a BLSS

Higher plants
With regard to closed systems, which require the regeneration of the full value of human food, the first choice for this role most probably falls on higher plants. Higher plants are an important carbohydrate source on Earth. However it remains difficult to produce a balanced diet when using only a limited set of plants, because they lack essential fatty acids and often have a poor protein content. Also, a closure of the whole system can only be achieved if the problem of inedible biomass, such as roots and leaves, is overcome, i.e. if the waste-material produced by the plants is recycled. Most of the organic wastes produced in BLSS based on higher plants originate from these plants. Higher plant compartments in a BLSS may not only serve as a provider of food, but the plants can also be used for atmosphere revitalisation, water regeneration (liquid management) and for psychological comfort of the crew, by providing an Earth-like environment

Plant physiology in space. It is generally recognised by crop physiologists that the nutritive value of plants grown in controlled environments (greenhouses, closed chambers) varies considerably, but can reach values that are similar to those of plants grown in field environments. Requirements and performance data can be estimated from terrestrial greenhouse plant production (i.e. a controlled environment). A summary of these values is given in Table 5.5. It can be noticed that the areas needed for water and O_2 regeneration are, respectively, about 20% and 40% of those required for food production.

The main goal of plant growth is to obtain a maximum crop yield. This yield mainly depends on the growth conditions, such as the incident photosynthetic photon flux (PPF), the carbon dioxide assimilation rate, the light requirements (photoperiod, intensity) or the area requirements. More research on both, the physical as well as the biological parameters (Table 5.6), is needed to utilise higher plants effectively in space-farming (greenhouse) systems. The crop yield may also be improved by manipulating the genotype of plants (genetic engineering). In this case, the sensitivity of the new plants to radiation and their susceptibility to mutations has to be studied.

Early research on plants for BLSS focused on the physical parameters, because the control of these factors is the prime requirement for a successful BLSS (NASA, 1982a; Salisbury, 1992). One of the most important physical parameter is light. Artificial light is easier to control and manage than natural light, but consumes a great deal of energy. The development of plants through a complete

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Table 5.5: Plant requirements and performances mean values (from Blüm & Kreuzberg, 1992)

Plant requirement	**Amount**
CO_2	40-300 g/m²/day
Water	5-10 kg/m²/day
Minerals	10-100 mg/m²
Lighting period	8-24 hours
Lighting power	13-170 W/m²
Plant production	**Amount**
O_2	30-220 g/m²/day
Transpiration Water	5-10 kg/m²/day
Dry edible biomass	20-40 g/m²/day
Dry inedible biomass	4-20 g/m²/day
Consumable	**Required area per person**
Water	3-5 m²
Oxygen	6-10 m²
Food	15-20 m²

life cycle, and the formation of viable seeds in microgravity, was conducted in the *Svet* greenhouse on board the Mir space station. In these experiments, viable seeds were produced but there was also a large number of abnormal seeds. In initial experiments on Mir in 1990, radishes and Chinese cabbage were grown in *Svet*. Although germination was lower and the flight plants grew considerably less, a radish root crop was produced for the first time in microgravity (but with only 31% of the fresh weight and 61% of the dry weight of the ground control plants). In a mission on Salyut-6, the self pollinator *Arabidopsis*, which grows on artificial soil, flowered in a plant growing chamber. This experiment demonstrated that it is possible to grow plants from seed to seed in weightless conditions. However, it must be stated that in most of the experiments in space, it was not possible to bring plants to flowering (e.g., onions on Salyut in 1978 and wheat on Mir in 1991).

Table 5.6: Physical and biological parameters to be taken into account in the development of space-farming systems (From: NASA, 1982a; Salisbury, 1992)

Physical parameters	**Biological parameters**
Water and nutrient delivery - growth media	Seeding establishment and seed coat shedding
Liquid transport to and from roots in hydroponics and/or aeroponics systems	Orientation of root, stem and leaves to maintain plant productivity
Oxygen and carbon dioxide solubility and diffusion in liquid and solid media	Flower initiation, pollen transfer and fertilisation
Air speed, humidity and CO_2 concentration	Accumulation of edible and inedible biomass Apical dominance
Light intensity, quality and duration of illumination	Plant production and exchange rates
Temperature	

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In order to investigate the effects of cosmic radiation on plants, experiments were performed on different plants (seeds and crops). Results from the 2 million seeds on board the US Long-Duration Exposure Facility (each received 3.5 to 7.3 Gy during the 6 years in orbit) and from seeds of lettuce, radish and garden cress stored onboard the Mir station, seem to show that there are no big differences between the growth of space-exposed seeds and Earth-based seeds. On the other hand, other results from both US and Russian spacecraft showed that under space conditions the number of mutations increases. Further experiments and observations are required to determine the effect of cosmic radiation on plants.

Plant growth and Higher Plant Compartment (HPC). The main parameters that need to be considered in an HPC design are (i) the cultivable surface, (ii) the volume required (from roots to canopy), (iii) the light (irradiance, photosynthetic efficiency, photoperiod), (iv) the atmosphere control (temperature, multiplication, fecundating, fruiting, flowering, soil culture, hydroponics culture, aeroponic e, humidity, pressure, air composition), and (v) the cultivation modes (seeding, vegetative culture) (NASA, 1982a; 1982b). The environmental light conditions were investigated by Hernandez & de Llanza (1994) in their studies for the definition of a closed and controlled HPC. Hydroponics cultures are considered suitable for plant growth in low gravity environment (Salisbury, 1992; NASA, 1989). The environmental differences between a spacecraft and a planet, e.g. Mars, require different HPC designs (Table 5.7).

In order to select plants appropriate for an HPC, many species were tested, in the 1960s and 1970s, for the effects of gravity, radiation and air composition. Later, a wide ranging set of experiments on nutrition, yields in different conditions, and monitoring of atmosphere, was carried out in different facilities, following the different BLSS projects (Table 5.8). Wheat (*Triticum aestivum L.*), soya beans (*Soja max.*), potatoes (*Soluanum tuberosum L.*), and lettuce (*Lactua sativa*) have mostly been used in experiments in preparation of a BLSS. In the three NASA centres (see Table 5.8), wheat, soya beans and lettuce were grown in hydroponics culture as well as in calcined clay substrate. In the US Breadboard Project, white potatoes, sweet potatoes, rice and peanuts were also tested (Wheeler, 1992; Drysdale et al., 1994). In BIOS-3 , carrots, beet, radish, tomatoes, cucumbers, sedge-nut, potatoes, onions, dill, and kohlrabi were grown (Gitelson & Mac Elroy, 1999). The Japanese CEEF higher plant chamber contained rice, soya beans, komatsuna, tomatoes and potatoes (Toki et al., 1994). The following crop species were identified by a group of specialists to be of major interest as human food sources in BLSS (NASA, 1982b):

- Group 1: Species that are commonly used as food plants and can provide the major nutritional needs of humans. It is important to choose the set of plants in order to obtain the best match to the crew's nutritional requirements.
- Group 2: Species with lower nutritional values but high psychological value (see also Section 4.4).

The species suggested for the two groups are listed in Table 5.9

Bacteria

Bacteria can often be found in association (symbiosis,...) with other biological components of a BLSS (e.g., as microflora on the human skin, or as symbiotic bacteria associated with plant roots). These bacteria cannot easily be controlled and may cause safety problems and mass balance problems (e.g., N2 formed by bacteria in symbiosis with plants roots). The bacterial populations are not really considered as subsystems in a BLSS.

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Table 5.7: HPC requirements for installation on a spacecraft or on a planet
Source: Hernandez & de Llanza 1994.

HPC on board a spacecraft	HPC on a planet
– a few, small, easy to cultivate, and highly productive plants	– a broader collection of cultivable plants
– only hydroponics culture	– combination of hydroponics cultures and use of soil from the planet
– artificial lighting	– use of sunlight and greenhouse effect
– extreme atmospheric closure	– free architecture and geometry of HPC and CELSS in general
	– modularity and diversity in the HPC configuration
– technical disposition adapted to the absence of gravity	– technical disposition adapted to the presence of gravity

However, bacteria (other than cyanobacteria that are treated in the previous algae section) are also an important element in closed ecosystems, especially because they are the main biological process for the mineralisation of organic compounds. In artificial ecosystems, bacteria provide the link between the human (more generally the waste producers in the loop) and the autotrophs. The two main functions of bacteria in artificial closed ecosystems are (i) the decomposition of human metabolites that are not assimilated by plants and (ii) the decomposition of autotrophic biosynthesis by-products that are not needed by humans (such as the inedible parts of plants). The bacteria involved in such processes are chemoheterotrophic (as methanogens), photoheterotrophic and chemo-autotrophic.

Table 5.8: Main international projects and studies of BLSS

Biological based system	Project name/Location/date	Project principles/Project results
Small closed ecological systems	C. Folsome. University of Hawaii (1967)	Sealed flask (100 ml-5 l) Multicultural aquatic solutions (biosynthetic decomposer) Energy + information exchange
	CEBAS (Closed Equilibrated Biological Aquatic System) [EU]	Five German zoological university institutes were involved in this task. Basically, it was designed as an aquarium for long-term zoological space research. The animal tank (zoological component – fish) was combined with an aquatic plant bioreactor, (botanical component), and with a bacteria filter (microbial component – ammonia oxidising bacteria). Ground test run and two spaceflights.
	ABS (Autonomous Biological System) [USA]	Closed aquatic life support system (vascular plants; invertebrate animals; algae; microbes).

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Table 5.8 (continued): Main International projects and studies of BLSS

	Paragon Space Development Corporation	9 months of accumulated flight testing (Shuttle 1996; Mir 1997 and 1998). Used as a model for the study of the effects of microgravity on the dynamic of ecological systems
Algae based system	US Air Force School for aviation medicine (1961) [USA]	Monkey/algae gas exchange Duration up to 50 hours Carbon monoxide accumulation
	Microterella [USA] Sanitary Research Laboratory and School of Public Health. University of California	Mice (1 to 4) – Algae – Microbial system Algae and microbial consortium form a biocenosis. Ground experiments run 1 to 6 weeks. Gas and liquid balance experiments. No toxic compound accumulation (mice still alive) Micronutriments not balanced (resupply needed)
	Algae gas exchanger for CELSS – [USSR – Russia]	Mouse/algae *(Chlorella)* Mass balance study of atmosphere revitalisation Control of the GEC by use of two nitrogen sources (nitrate and urea). Concept of a mouse/algae/wet air oxidiser system, for atmosphere revitalisation (closure between 97% and 100%)
	Gas exchanger [USA] (Eley & Myers, 1964)	Mouse/algae *(Chlorella)* Closed system experiments run 16 days and 24 days. System balanced for CO_2 at 0.3 to 0.7 % and limiting growth of algae. Complete balance in gas exchange difficult to obtain (GEC not equal to 1)
	Closed Equilibrated Biological System. [Japan] (Miyatake et al., 1999).	Four biological compartments system: zoological (man; animal); higher plants; algae(the life supporting component); microbial component. Algae *(Euglena gracilis)* deals with the O_2/CO_2 gas revitalisation. Photobioreactor for separation of gases in microgravity by using membranes was developed.
	Institute for Biomedical Problems (IBMP) and Institute of Physics (Krasnoyarsk) [USSR-Russia]	Studies of a thermophilic strain of *Chlorella vulgaris*. Since 1969, intensive flowing cultivation without degradation of the strain.
	BIOS 1 (1964-1965)	5 experiments allowing gas exchange and later water exchange in a sealed cabin (5 m^3) for a crew during 29-32 days with 3 *Chlorella* reactors (15 l each). Gas closure up to 90%. Diet 10% from algae
	MELiSSA [EU] (since 1989)	In its initial definition it was a 5 compartment system based on the N-cycle: 1 crew compartment, 2 microbial compartments, 2 algae compartments (*Spirulina platensis* and *Rhodospirillum rubrum*). Special efforts were focused on the mass balance analysis of the cycles, on the modelling and on control aspects for the biological compartments. Each compartment was studied and validated separately. Physical link of compartments was started in 1999. *(Cont.)*

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Table 5.8 (continued): Main International projects and studies of BLSS

	FEMME [EU]	2 compartment system: O_2 producer photosynthetic compartment (algae) and an O_2 consumer compartment (micro-organism). The objectives are: 1) to validate direct use of sun as light and energy supply for photosynthesis and thermal control 2) to validate the ability to store and reactivate microbial culture in space 3) to study the kinetic evolution of the ecosystem and the gas mass transfer
	Biorat [EU]	2 compartment system: an O_2 producer photosynthetic compartment (algae *Spirulina platensis*) and an O_2 consumer compartment (rat). The objectives are: 1) to evaluate a controlled algae growth in microgravity as core element for the consumer atmosphere management; 2) to validate the control approach (validated on ground based Biorat experiments)
Higher plant based systems	University of Logan (Utah) and Institute of Biomedical Problems (Moscow)	Ultra dwarf wheat 65 days from seed to harvest Growth tested on Mir (1995; 1997)
	NASA Ames Research Center	Salad Machine (1990): Test for crop candidate for LSS Terrestrial application for life system for Arctic and Antarctic bases
	Kennedy Space Center (KSC) [USA] (BLSS testing since 1985)	Advanced Life Support System Breadboard and Biomass Production Chamber (BPC)
	Johnson Space Center (JSC) [USA] ALS projects	Advanced Life Support Systems including physico-chemical systems The objectives of the ALS programme at the NASA JSC are: 1) to validate regenerative Life Support technologies 2) to develop technologies for LSS 3) to identify terrestrial application of Life Support technologies
	Lunar-Mars Life Support Test Project (LMMSTP)	Three phase test project for testing combination of biological (Variable Pressure Growth Chamber using hydroponics) and physico-chemical systems for a crew of four. Objectives include: 1) regenerative air revitalisation 2) water regenerative recovery system capable of recovering potable water from hygiene water, urine, and humidity condensate.
	BIO-plex (Advance Life Support System Integration Test Bed – ALSSIT) (1999)	In continuation of ALS breadboards test-bed, the objective of this sealed complex is to support large scale, long duration testing of integrated biological and physico-chemical regenerative life support systems with human test subjects under controlled conditions. Developed and tested for future Mars Missions

(Cont.)

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Table 5.8 (continued): Main International projects and studies of BLSS

	Institute of Physics (Krasnoyarsk) [USSR-Russia]	Environment regenerated by physico-chemical means
	Ground Experimental Complex (GEC) (1968) and BIOS 2 (1968-1969)	Greenhouse (15 m^2) with chlorella provide only 19 % of the crew requirements. 3 link (Human-algae-higher plant) and 4 link (Human-algae-higher plant-microbial). Up to 80-90% of the food produced, but physico-chemical system required because of imbalance of the system for other compounds (O_2, CO_2, ...).
	BIOS 3 (1974-1985)	Sealed complex improving systems developed in BIOS 2 and used to conduct experiments on human life support in biological LSS, lasting up to half a year. Up to 80%-90% of closure.
	Mir Space Station (1995-1997)	Some crops (such as onions) tested as food complement.
	Svet	Growth of the ultra-dwarf wheat in the *Svet* phytotron.
	MELiSSA [EU] University of Guelph [Canada]	A sixth compartment (higher plant) was added to the definition of the system to improve the diet for the crew.
	CEEF (Closed Ecology Experiment Facility) [Japan] (1977)	The CEEF concept really started in 1990 with the creation of the Institute for Environment Science. Supported by the largest industrial companies of Japan, taking part in manufacturing equipment and elaborating technology, the construction of CEEF is to be completed in 2000. It consists of subsystems for the cultivation of plants, closed animal breeding and habitat module, geosphere and hydrosphere module. The system is designed for one man.
	Biosphere 2 [USA] (1984)	Not a scientific experiment in a strict sense. Eight people in a sealed (?) complex for two years. System defined as a miniature of the Earth's biotope (desert, sea, forest...) Failed to find a dynamic steady-state.
Biological Waste Treatment system	Kennedy Space Center [USA]	Treatment of inedible biomass for: 1) mineral recovery, 2) alternative food production option (fungi; yeast; fish). Liquid waste (grey water) directly to plant growth systems.
	MELiSSA [EU] (since 1989)	In its design , the 2 first compartments of the MELiSSA loop are dedicated to biological waste treatment by anaerobic biological processes.
	CEEF [Japan]	CEEF includes liquid and waste recycling within all the modules.
Animals (as food element of BLSS)	CEEF [Japan]	Animals are a part of the systems (Animal breeding module – goats; hydrosphere module)
	Biosphere [USA]	As a miniature of a biotope, the system includes animals (fish, chickens...).

Reference sources: Eckart, 1994; Gitelson & MacElroy, 1999; ALS 1999; ICES, 2000; Eley & Myers, 1964; Smernoff et al., 1987; Myatake et al., 1999.

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Table 5.9: Plants selected for HPC (NASA, 1982b)

Group 1 – Nutritional interest	
Wheat	High calorific density
	Basis of many different types of food
	High edible portion of biomass (harvest index)
Rice	High calorific density
	8% of nutritionally balanced protein, phosphorous, iron, thiamine and niacin
White potatoes	High calorific food
	Minimum processing
	High carbohydrate concentration and same protein concentration as rice
	Good source of vitamins
Sweet potatoes	Same as white potatoes
	Adapted to warm environment
	30% more carbohydrate than white potatoes
	Leaves and young shoots are edible
	Vine-type growth of the stem can be a disadvantage
Soya beans	Major source of dietary proteins
Peanuts	Major source of proteins
	Contain a lot of oil
	Complex growing and harvesting procedures
Lettuce	Vitamins A and C
Sugar beet	Provide sugar
	Can be eaten raw. Tops are edible
Group 2 – Psychological interest	
Taro	Tropical crop
Winged beans	Can be eaten (protein source)
	Adapted to higher temperature
Broccoli	Contains vitamins A, B1, B2, B7 and C
Strawberries	Very high psychological value
	Contain vitamins B2, B7 and C
Onion	Low nutritional value
Peas	Protein source
	Large quantities of minerals
	Require special culture system

There are two possible pathways for the destruction of organic substances, (i) aerobic and (ii) anaerobic. Anaerobic degradation is a more universal process because many of the substances to be degraded are in the oxidised state. Their degradation requires reduction reactions, which are only possible in anaerobic processes, but these are complex, require biocenosis and produce a wide spectrum of gaseous and liquid products that require further utilisation (methane, hydrogen, organic acids and others). The advantage of biological anaerobic processes, both for space and terrestrial application, is their low energy consumption and, in some cases, they are their own energy producers. Life support systems involving autonomous anaerobic bacterial subsystems for waste and water treatment have been proposed by Mergeay et al. (1988) and Myatake et al. (2000).

Aerobic processes (activated-sludge-like processes) result in quick and deep decomposition of metabolites. They give more directly useable products (such as CO_2) for autotrophs than anaerobic processes, but require intensive aeration to be

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efficient. In addition, they have higher energy requirements than anaerobic processes. The oxygen requirement of such processes necessitates careful control of the mass balance fluxes with other subsystems of the ecosystem for oxygen production (autotroph: algae; plants) and consumption (crew). Such processes were tested and used in BIOS 3.

Yeasts and other fungi

Higher fungi are promising for the mineralisation of inedible plant parts, especially for the problems encountered with the degradation of polymerised compounds like cellulose or lignin. Fungi can also contribute to the food of the crew as an interesting source of minerals. Even though fungi were identified in the BIOS 3 biocenosis as a part of the waste degradation component, few studies exist concerning the integration of fungi as a subsystem in artificial closed ecosystems. In Europe, in the FOOD project (Fungus On Orbit Demonstration), which started in 1999, the feasibility has been investigated of the application of fungi for fibre degradation (Soler-Rivas et al., 2000).

Animals

Animals are mainly a source of proteins, essential fat, and vitamins. Animals can be introduced into closed systems as a heterotrophic link, at the cost of significantly complicating the system, increasing its size and reducing the energy efficiency by several degrees. It is then obvious to select animals with small mass and a short life cycle. Aquaculture systems seem the most promising, as they can be developed as a quite autonomous ecosystem inside the ecosystem containing the crew (e.g., as CEBAS, ABS systems , see Table 5.8).

5.3.2 Available Biological Life Support Systems

Table 5.8 gives an overview of the main past and present international projects and studies in relation to BLSS. Although this overview is not comprehensive, it gives the state of the art in terms of system choices (e.g., algae, higher plants), and in terms of technology (flight experiments, projects, breadboards). The main projects, actually considered by the International Advanced Life Support Working Group are Bioplex [USA], CEEF [Japan] and MELiSSA [EU].

Complete closure of a BLSS has not yet been achieved by means of an artificial biological ecosystem. Resupply (or storage) and/or physico-chemical processes have always been necessary. In the Earth's biosphere itself, the biological cycles are linked to geological and hydrological cycles. These observations suggest that a completely closed ecosystem cannot easily be obtained artificially by using only biological components: physico-chemical subsystems will remain an essential part of an ECLSS. The potable water is one typical example: it is the result of both biological activities (decreasing the organic and mineral load) and hydrological activities (by natural filtration). In artificial ecosystems similar processes must be established.

5.3.3 Recommended research and development for BLSS on exploratory missions

Two main criteria have to be considered when choosing biological subsystems as part of life support systems for long-term exploratory missions:

- the duration of the mission, which is linked to the mass of consumables required to sustain the crew; and
- the distance from Earth

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These constraints are different for "spacecraft" missions and "lander" missions. For the interplanetary spacecraft, the volume, mass, launch cost, microgravity conditions and energy cost are important parameters, while for a base on the Moon or a habitat on Mars the reliability over very long time spans and the closure of the systems become the more important elements.

As explained in Section 5.3.1, there is a wide range of biological components that can be used in an ECLSS. There are many interrelations between each component and subsystem (biological and/or physico-chemical) and so a biological life support system must be studied as a whole and not as individual elements. This is true for the calculation of the closure of the system (which gives the reduction of the mass of the consumables) and for the calculation of the overall mass, volume and area 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 include in the choices for the design of system. The reliability of the system in case of the failure of one of its elements (biomass death or plant diseases) must also be considered. From a failure point of view, systems with a short life cycle, which can be restarted quickly, would be the preferred choice. For safety and reliability, a biological life support system must not be based on a single biological component.

At the present time, the main space agencies have quite different strategies for the development of BLSS, which are more complementary than conflicting: NASA has focused its studies on higher plants, associated with physico-chemical processes for the oxidation of the inedible parts of the plants; ESA concentrates on projects based on microbial and algae components, associated with higher plants (as a food provider) and physico-chemical processes; Japan, with the CEEF, has a strategy more oriented towards terrestrial applications and large ground bases, but has also started a project similar to those developed by ESA.

From the present knowledge from the existing BLSS and on the biological components that can be included in a BLSS the following recommendations can be made:

- Higher plants would be the core for food production in a BLSS, but the difficulty of controlling their biological activity and the manpower they require do not favour their use for small volume systems such as a spacecraft. Nevertheless they would be the core of biological systems for permanent bases.
- Algae are very promising components for atmospheric regeneration. The biomass produced can be used as a food complement (proteins, vitamins). The possibility to have a precise control of the process makes it a promising alternative or complement to physico/chemical regeneration of atmosphere. The main problem encountered concerns the Gas Exchange Coefficient between the O_2 consumer and the O_2 producers (algae). Algae are also present in biocenosis for waste treatment (BIOS-3) and in aquatic ecosystems.
- 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 components 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 terms of the 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 buildings...).

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5.4 Environmental Monitoring

5.4.1 Environmental components that need monitoring

The basic purpose of monitoring is to diagnose and feed back information to a warning or control procedure, so that the risk of unacceptable exposures of the crew is minimised. Environmental monitoring (and control) encompasses the internal environment including the atmosphere, water supplies and all surfaces of a spacecraft or extraterrestrial habitat occupied by humans. The expression 'monitoring' means to assess the status of all these areas over time to ensure that the conditions are maintained within predefined limits. The general requirements for environmental monitoring systems are:

- robustness,
- high reliability,
- stability,
- rapid response,
- a high degree of autonomy, and
- ease of calibration and maintenance.

Air

Table 5.10 summarise the most important parameters to be monitored in the air of a spacecraft or extraterrestrial habitat. Monitoring of major components, as well as of trace species, of the internal atmosphere is necessary to maintain the health, performance and comfort of the crew. In addition, impairment of the performance of sensitive payloads and equipment has to be avoided. In Space Shuttle and Mir missions a variety of chemical contaminants of the cabin air have been identified and quantified. In future longer-duration space missions, similar but more complex mixtures of contaminants can be expected. Therefore monitoring and control systems should be able to adapt to new conditions. The SMACs (Spacecraft Maximum Allowable Concentrations) for a number of selected contaminants have been defined by NASA for different exposure times of the crew (NASA 1966; NRC, 1994; 1996; 1997; 2000). These are the drivers for the development of new monitoring and also contaminant removal techniques. In addition to chemical contaminants, airborne microbiological contaminants should be monitored to minimise potential hazards from infectious diseases, allergies and biodegradation of materials. The quantities and sizes of particles in the air must also be monitored.

Water

For water quality SMCLs (Spacecraft Maximum Contaminant Levels) have been defined by NASA for potable and hygiene water. These include physical parameters and threshold values for inorganic and organic compounds as well as for microbial contaminants (Table 5.11). The exposure limits do not take into consideration the duration of exposure, in contrast to the SMACs for air-borne contaminants (NASA 1996; NRC 1994, 1996, 1997, 2000).

Surfaces

In the confined environment of a spacecraft or extraterrestrial habitat, moist surfaces have to be scanned for microbial contamination and for chemical contamination in the event of accidents/spills.

Microbial Contamination of Air, Water, Surfaces

Microbial contamination control is fundamental for a successful space mission and for the safety and well-being of the crew. Accumulation of microorganisms in spacecraft carries the danger of infectious diseases of crew members, allergies, damage to materials and instruments, selection of mutant strains, production of

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toxic metabolites and degradation of environmental hygiene. The microorganisms have to be identified *in-situ* or through culture. A preliminary list of microbial contamination requirements has been produced by NASA.

Up to now, biofilm forming species, plant pathogens and opportunistic pathogens have not been taken into consideration. Standard methods for the cultivation of bacteria and fungi have been defined. As many new methods for the determination and quantification of microorganisms are under development in the area of molecular biology, the requirements have to be adapted regularly to the state of the art.

Air which is recycled over long periods in the closed environment of a spacecraft is the most important medium for the distribution of contamination. Therefore it is very important to quantitatively monitor the microbiological contamination in the air, to evaluate the total load of microorganisms.

5.4.2 Available monitoring technologies

Different systems have been developed for monitoring the cabin air (NASA, 1997; ESA, 1999a; ICES, 2000). Trace gases can be quantified with a FTIR (Fourier-Transform Infrared Spectrometer) instrument, by the detection of gas-specific absorption characteristics in the infrared range of the electromagnetic spectrum. If necessary, additional enrichment systems must be used in the different modules of the spacecraft. This system has been tested in breadboard studies. For the determination of specific compounds, e.g. formaldehyde, diode-laser-based gas sensors have been tested in the laboratory. If tunable diode lasers were used, this method could be used to detect a variety of compounds. A complementary alternative is the utilisation of quadrupole mass spectrometer array instruments with and without GC (gas chromatography). These have so far only been used in laboratory tests. IMS (Ion Mobility Spectrometry) has been used for real-time monitoring of hydrazine and other compounds onboard submarines and could be adapted for use in spacecraft. Water vapour in the atmosphere can be monitored with a dew point hygrometer and this has been demonstrated in tests with radiosonde balloons and in aircraft. In emergency cases, simple and easy to handle tests have to be used, e.g. Dräger tubes for the qualitative (and wherever possible quantitative) determination of single species.

In the case of water monitoring, less innovative space-related technological development has been performed up to now. The assessment of basic water quality parameters is mainly done by classical methods established for application on Earth, with on-line and off-line sensors.

In addition to physico-chemical monitoring techniques, bioassays and biosensors will, in the future, be used for environmental monitoring of air, water, newly produced food etc. in spacecraft and extraterrestrial habitats. Biosensors are defined as analytical devices which incorporate biological material (tissue, microorganisms, organelles, cell receptors, enzymes, antibodies, nucleic acids etc.), biologically-derived material or biomimics, intimately associated with, or integrated within, a physico-chemical transducer or transducing microsystem, which may be optical, electro-chemical, thermometric, piezoelectric or magnetic. Biosensors usually produce a digital electronic signal that is proportional to the concentration of a specific analyte or group of analytes. The devices can be configured to produce a continuous signal or to yield single measurements. Biosensors are distinct from bioassays, in which the transducer is not an integral part of the analytical system. Biosensors are particularly valuable for

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Table 5.10: Parameters to be monitored in the spacecraft air

Parameters	Examples	Recommended type of monitoring
Physical	temperature	continuous
	pressure	continuous
	particle 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

environmental monitoring when they provide either 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 that are difficult to measure using conventional methods. Biosensors may also have a 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 miniaturisation and integration into multisensor arrays, to facilitate analysis via, for example, neuron networks and chemometrics. Biosensors are certainly 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 *in-situ* measurement at different locations in a spacecraft, make them particularly attractive for use in such environmental monitoring situations.

Table 5.11: Parameters to be monitored in potable and hygiene water

Parameters	Examples	Recommended type of monitoring
Basic water quality	conductivity	continuous
	turbidity	continuous
	pH	continuous
	free and dissolved gases	continuous
	TOC (total organic carbon)	continuous
	colour	continuous
	dissolved solids	continuous
	biocides	continuous
Chemical	inorganic substances, e.g. transition metal ions	periodical
	organic substances	periodical
	specific hazardous chemicals from payload experiments, fluid systems, waste storage	periodical
Biological	microbial species and counts	periodical

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One example for a first biosensor test battery, selected for the ISS in the MCS (modular cultivation system), is TRIPLE-LUX (PI: B. Hock, Munich), in which the signal of gene, immune and cellular responses to the combined action of radiation, microgravity and other spaceflight parameters will be translated into bioluminescence or chemiluminescence as a rapid optical reporter system.

5.4.3 Recommended research and development

As a general requirement for environmental monitoring in a spacecraft or an extraterrestrial habitat it is necessary to develop small robust integrated systems. For monitoring of potentially dangerous chemicals in air, in water, or on surfaces, microsensors have to be designed which act in a coordinated way and which are connected to an alarm feedback system. For the examination of the spacecraft/habitat microbial fauna, autonomously operating microsystems for the quantification of microbial contaminants of air, water and surfaces, as well as autonomously operating identification systems for these contaminants, have to be developed, together with adequate cleaning/sterilisation procedures. In long-term missions, biological LSS will be used, in which the biological components may undergo changes in their metabolism caused by chemical pollutants and/or toxic metabolites. It is therefore necessary to define biomarkers for the control of the state of a biological LSS and to develop autonomously operating biosensors and bioassays for these biomarkers. In addition, the genetic identity, integrity and stability of the biological components of an LSS have to be assured by autonomously operating measuring systems for these biomarkers. Also, for the maintenance of the health of the human crew, biomarkers have to be identified as indicators of change within the organism, that link exposure to a chemical to subsequent development of adverse health effects. Biomarkers of exposure to pollutants may contain the chemical itself or a metabolic fragment and thus are chemical-specific. They include the totality of subclincal and clinical signs of chemically induced disease states and serve as predictors of serious effects or late-ocurring effects. Other human biomarkers can be used to indicate the individual susceptibility to the effects of exposure to pollutants and to predict which persons are most likely to be at greatest risk as spacecraft/habitat crew members. All these future developments will be based on existing knowledge, especially in the rapidly growing area of molecular biology/biotechnology. New efforts are required for the miniaturisation, integration and control of the individual components, using microsystem technology and bioinformatics.

5.5 Utilisation of natural resources

5.5.1 Introduction

There is a strong need to investigate how space resources may improve living conditions on Earth and in space. In particular, robotic and manned space missions could profit from the utilisation of natural resources on nearby planetary bodies. One of the most attractive options appears to be the production of propellants and life support consumables from materials found outside the Earth's gravity well, for example on the Moon or on 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. The advantage is immediately apparent from the fact that up to 90% of the total mass of conventional spacecraft consists of propellants. 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

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(ECLSS) could also benefit from extraterrestrial resources, depending on the degree of closure of the systems. Products derived from these resources could, for instance, replace losses due to consumption, leaks or extra-vehicular activities (EVAs). 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.

Due to the complexity and expected synergies of the processes involved, it seems quite reasonable to discuss the on-site production of life support consumables in combination with propellant production. Only in special cases will dedicated ISRU (In-Situ Resources Utilisation) products and applications for life support be economical. It is therefore expected that important mass and cost savings could eventually be obtained for manned missions, as well as major improvements of mission reliability due to partial self-sufficiency. Achieving these goals requires a detailed understanding of the lunar and martian environment and resources, as well as insights into the mining technology and chemical processing that must be used to generate the necessary products in a mass- and energy-efficient manner. These processes involve chemical reactions, multiphase flows, and phase changes. The scaling laws for these processes are often poorly understood even for our terrestrial environment.

The following sections discuss various on-site resource extraction and utilisation concepts that are envisioned for lunar and martian exploration. The Moon and Mars are completely different with respect to the presence of volatiles on their surfaces. The lunar surface is extremely dry and an atmosphere is practically absent, whereas Mars has a thin atmosphere which contains up to 95% CO_2. Numerous processes have been proposed for the separation of oxygen from the lunar regolith and several of these, such as the reduction of ilmenite, have been tested experimentally. Four of the most promising processes are discussed below. The assessment of lunar oxygen utilisation concepts is considered within a scenario for a permanent lunar base. In contrast, the production of propellants and life support consumables on Mars is evaluated in the context of a single or a few subsequent exploratory manned Mars missions. Three different processes are described for producing propellants and life-support consumables on Mars. The extraction of oxygen from the martian atmosphere and the production of methane and water with imported hydrogen appear to be the most viable options, based on the fact that they can be derived from existing technology, e.g., in the field of life-support systems.

5.5.2 Resources of the Moon and Mars

Lunar Resources

The lunar surface rocks and the fine-grained regolith are similar in chemical composition to terrestrial rocks. They consist mainly of silicate material with an oxygen content between 40 and 45 wt.% (Table 5.12). Oxygen is the most abundant element on the Moon, but it is strongly bound in the silicate/oxide minerals.

In principle, the following lunar resources could be exploited:

- oxygen bound in silicate/oxide minerals of the lunar regolith (Table 5.13);
- volatiles in the regolith (e.g. solar wind implanted hydrogen, carbon etc. (Table 5.14));
- on-site materials for the production of advanced fuel compounds (e.g. silane, aluminum); soil as the plant growth medium in greenhouses (t.b.c. by future experiments) or as radiation shielding material;

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Table 5.12: Chemical composition of lunar mare soil data from Apollo 12 samples.

Element	O	Fe	Al	Ca	Mg	Si	Ti+other
wt %	43	12	7	8	6	22	2

Table 5.13: Typical average mineral abundances in lunar regolith data from Apollo 17 samples.

Mineral	Pyroxene $(Mg,Fe,Ca)SiO_3$	Plagioclase $CaAl_2Si_2O_8$/ $NaAlSi_3O_8$	Ilmenite $(Fe,Mg)TiO_3$	Olivine $(Fe,Mg)_2SiO_4$	Glasses (composition similar to Table 5.12)
wt. %	31	16	6	1	46

Table 5.14: Lunar volatiles in equatorial regolith, data from Apollo 11 samples

Element	H	C	N	^4He	^3He
wt. ppm	0.3 – 100	3 – 300	9 – 250	1 – 20	0.0005 – 0.05

- possibly, increased quantities of water/hydrogen in the regolith near the polar regions (according to data from Clementine and Lunar Prospector missions).

The occurrence of water/hydrogen in the regolith near the lunar poles is a matter of some discussion. The existence of water ice is not strictly proven. The Prospector neutron spectrometer data only allow an estimate of the proton content in the polar regolith. The corresponding numbers are larger than those for equatorial solar-wind-implanted hydrogen (well known from Apollo samples) by a factor of 10 to 20 (Schmitt et al., 2000), corresponding to a relative hydrogen portion of 0.1 to 0.2 wt.%. It is far from clear whether this hydrogen is bound in H_2O molecules (possibly deposited by cometary impacts) or just solar-wind-implanted. Certainly, the solar wind exposure and storage within the regolith will depend on the lunar latitude and longitude, but the details of the processes involved are not yet completely understood. For example, losses of adsorbed solar wind hydrogen within the regolith – due to diurnal heating – can be expected to be much lower in the cold polar regions. The important question of whether major mineable quantities of H_2O, CO_2, CO etc. (e.g. as ice crystals) exist in permanently shaded polar regions will probably only be solved by on-site investigations during robotic or manned missions.

In any case, the acquisition of those implanted volatiles would require immense efforts for mining many tons of regolith, and heating it to temperatures up to 1000°C, to get a significant amount of gas. Typical gas release patterns, in the temperature range from 50 to 1200°C, from Apollo-11 samples (cf. Table 5.14) showed only minor quantities of H_2, N_2, H_2O, CO_2, CO, He, O_2, etc. (Gibson & Johnson, 1971). Afterwards, the extracted gas must be cooled down for separation of the different species by fractionate distillation (yields would be only about 0.1 to 1 kg of H_2, C or N_2 per ton of regolith.

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Table 5.15: Average composition of the martian atmosphere

Compound	Volume
CO_2	95.32%
N_2	2.7%
Ar	1.6%
O_2	0.13%
CO	0.07%
H_2O	0.03%
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.03 ppm

Source: Owen et.al., 1977

The production of propellants and life support consumables on the Moon will therefore concentrate mainly on the liberation of oxygen from the regolith.

Martian Resources

In contrast to the Moon, Mars has a considerable atmosphere even if it is thin. The composition is given in Table 5.15. The pressure was measured at the two Viking sites and varied typically between 700 and 1000 Pa (7-10 mbar), so liquid water may not be stable on the surface. There are major polar ice deposits, consisting at least of H_2O and CO_2, but placing a Mars base near the poles might be extremely difficult. Within the regolith and deeper in the ground there could be hydrated silicates, carbonates and permafrost layers composed of H_2O and CO_2. This must be explored further. Mars therefore has many more resources (especially volatiles) available for use in a life support system, than the Moon, and it is much easier to compress a gas from the atmosphere and produce oxygen and other consumables, including propellants, than to mine the regolith. Furthermore, there is already a wealth of experience available (also in Europe) from life support technologies for submarines and manned spaceflight which could be used synergetically, for instance Astrium's Air Revitalisation System ARES for three astronauts (regenerative CO_2 adsorption and delivery at ambient pressure to a Sabatier reactor, with subsequent water electrolysis, O_2 generation and H_2 recycling) (see also Section 5.2). In the future, missions to Mars may rely heavily on *in-stitu* resources utilisation (ISRU) as a key technology. Such methods could be applied, in both robotic sample return missions and manned missions, to produce the propellants needed for a return to Earth.

In principle, the following martian resources could be exploited:

- atmospheric compounds;
- water ice and frozen CO_2 from the polar caps;
- ground water (permafrost below the surface);
- martian soil (e.g. for radiation shielding, extraction of volatiles or use in greenhouses).

Based, for example, on the well known Sabatier process, which allows the decomposition of atmospheric CO_2 with imported hydrogen, the production of oxygen and methane for propellants and of water for life support is most promising and the easiest to perform. These options will be considered in more detail below. The exploitation of other resources besides the atmosphere either

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appears to be too complex (e.g. requiring handling and processing/heating of large quantities of ice in the difficult polar environment) or remains speculative (e.g. ground-permafrost). The first step would be to compress the atmosphere – e.g. to several bars – using a dust filter on the pump intake. Next, a distillation step (liquefying the different components) would lead to a separation/purification (e.g. CO_2 liquefaction around -50°C at 7 bars). A dedicated demonstration experiment for Mars atmosphere compression (sorption compressor) and oxygen generation – called Mars In-Situ Propellant Production Precursor (MIP) – was planned for the now postponed US Mars 2001 Surveyor Lander mission (Kaplan et al., 1999).

5.5.3 Available technologies

Lunar oxygen processing concepts

More than twenty methods have been proposed for the production of lunar oxygen (Taylor & Carrier, 1993) including chemical, electrochemical and thermochemical processes. Most require several reagents (Table 5.16) and high temperature. Only the production of oxygen by thermochemical or electrochemical processes, e.g. magma electrolysis and pyrolysis, can be performed without an additional reagent. Among these methods, carbothermal reduction with methane, ilmenite/glass reduction with hydrogen, oxidation with fluorine and pyrolysis/vapour phase reduction have been assessed as the most promising (ESA, 1999b).

Carbothermal reduction using methane (at ≈ 1600°C). The carbothermal process includes the following three steps (Rosenberg, 1998):

Step 1: Reduction of silicates using methane
Step 2: Recovery of methane and water production

$$Mg_2SiO_4 + 2\,CH_4 \xrightarrow{1600°C} 2\,MgO + Si + \mathbf{4\,H_2} + 2\,CO \qquad (5.5\text{-}1)$$

Step 3: Water electrolysis and hydrogen recovery (reagent recovery)

$$2\,CO + \mathbf{6\,H_2} \xrightarrow[\sim 900°C]{Ni\ catalyst/} 2\,CH_4 + 2\,H_2O \qquad (5.5\text{-}2)$$

This process allows the use of unbeneficiated lunar mare and highland materials,

$$2\,H_2O \xrightarrow{electrolysis} \mathbf{2\,H_2} + O_2 \qquad (5.5\text{-}3)$$

because silicates are an abundant component of lunar soil. In addition, steps 2 and 3 have been demonstrated with an efficiency of ~100%. As a 3-step-process, carbothermal reduction promises significant oxygen yields (of about 20 wt.%) and only few processing difficulties. The formation of highly stable silicon carbides (SiC) as a side product, resulting in carbon losses within the processing cycle, has been found to occur at reasonably low rates. Oxygen production from lunar materials by carbothermal reduction therefore appears to be even more promising than the reduction of ilmenite or lunar glasses using hydrogen (see below) because the oxygen yield is higher and there is no need for feedstock beneficiation.

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Reduction of ilmenite/glass using hydrogen (at ≈ 1000 °C). The reduction of ilmenite-rich mare soil, or volcanic glasses, with hydrogen at about 1000°C is a process favoured by NASA (Taylor & Carrier, 1993; Rosenberg, 1998). The final product is water, which can be electrolysed or used for life support. This process is relatively simple, but the oxygen yields by ilmenite reduction are small (in the range of 3 – 4 wt.%). Slightly higher oxygen yields (5 – 6 wt.%) are reached by using lunar glass, which contains up to 20 wt.% of ferrous (II) oxide:

Step 1: Reduction of ferrous oxide (in form of ilmenite and/or lunar glass)

$$FeOTiO_2 + H_2 \xrightarrow{1000°C} Fe + H_2O + TiO_2 \qquad (5.5\text{-}4)$$

Step 2: Water electrolysis and hydrogen recovery (reagent recovery)

$$H_2O \xrightarrow{\text{electrolysis}} H_2 + 1/2\ O_2 \qquad (5.5\text{-}5)$$

In reaction (5.5-4), the main products are water vapour, which has to be condensed, iron slag and titanium oxide. In a second step molecular oxygen is released and hydrogen is recovered from the water by electrolysis (5.5-5), to be used for further reduction of the ferrous oxide. This processing concept is not complicated with respect to its chemistry and has been experimentally well established in industrial applications. However, an efficient closed processing cycle strongly depends on the availability of lunar raw material with high concentrations of ferrous oxide in the form

Table 5.16: Processing methods and reagents required for lunar oxygen production.

	Oxygen processing concept	**Reagent**
Solid/Gas Interaction	Ilmenite/Glass Reduction with Hydrogen*	H_2
	Ilmenite Reduction with Carbon monoxide	CO
	Ilmenite Reduction with Methane	CH_4
	Reduction of Metal oxides	H_2S
	Oxidation with Fluorine*	F_2
	Carbochlorination	C, Cl_2
	Chlorine Plasma Reduction	Cl_2
	Carbothermal Reduction with Methane*	CH_4
	Magma Partial Oxidation	(HCl, H_2O)
	Reduction of Ilmenite using metals	Li; Na
Aqueous Solutions	Hydrofluoric Acid Dissolution	HF, H_2O
	Sulphuric Acid Dissolution	H_2SO_4, H_2O
Electrochemical Process	Silicate/Oxide Melt Electrolysis	
	Molten Silicate Electrolysis	Pt (Anodes)
	Fluxed Molten Silicate Electrolysis	Pt, LiF-CaF_2
	Caustic Dissolution and Electrolysis	NaOH
Thermochemical Process	Pyrolysis/Vapour Phase Reduction*	—

*) *assessed as most promising concepts*

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of glass and/or ilmenite or comparable minerals. Therefore, considerable beneficiation of lunar soil may be necessary. Acquiring a feedstock that is ilmenite-rich must concentrate on high-titanium mare ore such as mare basalts. In addition, the presence of sulphide minerals, such as troilite (FeS) or pyrite (FeS_2), that are associated with ilmenite in mare soil, may lead to the formation of hydrogen sulphide, H_2S, which has to be removed from the gaseous product stream.

Hydrogen reduction of ilmenite has been successfully demonstrated in the laboratory. The process temperatures are comparatively low, 700°C to 1000°C, so heat exchange and energy requirements are modest. Experimental results indicate a low conversion from hydrogen into water during the reduction. The reaction rate decreases at lower temperatures and, in this case, the gas flow has to be increased simultaneously. Hydrogen diffusion into lunar ilmenite decreases with the ongoing reaction, because of the *Fe-coating* of unreacted ilmenite. Iron slag and titanium oxide cover the unreacted ilmenite and no further reduction by hydrogen is possible. Ferrous (II) oxide in lunar glasses is thermochemically less stable than silicate minerals. Although the reaction kinetics are more rapid, the phenomenon of *Fe-coating* still remains.

Oxidation with fluorine (at ≈500 °C). Fluorine is the most reactive element known and capable of oxidising even oxygen in its compounds, as shown in the general redox reaction:

$$Me^{x+}\,O^{2-} + F^0_2 \longrightarrow 1/2\,O^0_2 + Me^{x+}F^-_2 \qquad (5.5\text{-}6)$$

with $Me^{x+}O^{2-} = Fe^{+II}O^{-II}$, $Mg^{+II}_2Si^{+IV}O^{-II}_4$ etc.

In reaction (5.5-6), oxygen is liberated in the first step. The particular steps for the liberation of oxygen from oxides and silicates of lunar mare and highland regolith by fluorination, including fluorine recovery, are as follows (Seboldt et al., 1993; Lingner et al., 1993, Reichert et al., 1994; Seboldt et al., 1994; Koenies, 1998):

Step 1: Fluorination and oxygen liberation

$$Ca\,(Al\,SiO_4)_2 + 8\,F_2 \xrightarrow{500°C} 4\,O_2\uparrow + CaF_2 + 2\,AlF_3, + \mathbf{2\,SiF_4}\uparrow \qquad (5.5\text{-}7)$$

Step 2: Electrolysis of molten metalfluorides using silicon anodes

$$CaF_2 + 2\,AlF_3 \xrightarrow[900°C/Si]{electrolysis} Ca + 2Al + \mathbf{2\,SiF_4}\uparrow \qquad (5.5\text{-}8)$$

Step 3: Thermal decomposition of S_iF_4 on platinum surface at 1600°C (F_2 recovery)

$$4\,SiF_4 \xrightarrow{1600°C/Pt} 4\,Si + 8\,F_2 \qquad (5.5\text{-}9)$$

The liberation of oxygen by fluorination of different lunar materials (silicates and oxides) has been demonstrated to nearly reach completion. However, recycling of fluorine is complicated due to side products (metal fluorides and gaseous fluorides) which are extremely stable. Two recycling steps are therefore necessary to regain elemental fluorine for further use in the liberation of oxygen, and the overall process contains three steps. Electrolysis of different molten metal

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fluorides using semiconductor-anodes (e.g. Si) releases SiF_4 instead of elemental fluorine. SiF_4 has no corrosive properties, even at high temperatures, so that losses of fluorine by corrosion of reactor materials can be excluded. The resulting SiF_4 is combined with SiF_4 from reaction (5.5-7) and elemental fluorine can be obtained by thermal decomposition on a platinum surface at 1600°C. Except for this surface reaction, fluorination and melt electrolysis have been carried out on a laboratory scale, with at least 80 % conversion/recycling rates. The principle of thermal decomposition of SiF_4 into its elements has been demonstrated (Koenies, 1998). Nevertheless, further experimental investigations of reactions (5.5-7) to (5.5-9) are necessary, to estimate reaction rates in a scaled-up process. The fluorination process is promising as it offers the highest oxygen yields of all proposed processing concepts and a practicable recycling concept with a small number of steps.

Vapour phase reduction (pyrolysis) (at ≈2000°C). High temperatures, in the range of 2000°C, are needed to vaporise lunar feedstock (reaction 5.5-10a) and to induce thermal dissociation of oxides and/or silicate minerals into sub-oxides and elemental oxygen (reaction 5.5-10b). The second – oxygen releasing – step of this process is the condensation of the gas mix, thereby separating oxygen from condensed sub-oxides:

Step 1: Vapourisation and thermal dissociation

$$SiO_{2\,(solid)} \xrightarrow{2000°C} SiO_{2\,(gaseous)} \qquad (5.5\text{-}10a)$$

$$2\,SiO_{2\,(gaseous)} \underset{recombination}{\overset{dissociation/}{\longleftrightarrow}} 2\,SiO_{(gaseous)} + O_2 \qquad (5.5\text{-}10b)$$

Step 2: Rapid condensation of gas mix and oxygen release

$$2\,SiO_{(gaseous)} + O_2 \longrightarrow 2\,SiO_{2\,(solid)} + O_2 \qquad (5.5\text{-}11)$$

In this process, the condensation step (5.5-11) has to be faster than the recombination of monoxide compounds with oxygen in the gas phase (5.5-10b). Therefore rapid cooling is critical for the reaction rates and oxygen yields. In addition, condensed monoxides may cover the cooling surface. The cooling capacity is decreased by this monoxide layer and efficient condensation is hampered by decreasing heat exchange rates. The oxygen yields of vapour phase pyrolysis are theoretically in the range of 20% to 50% of the total oxygen content. Experiments to identify the vapour-phase species have been carried out by Senior (1993) on several lunar feedstocks. Vapour-phase pyrolysis shows advantages with respect to processes that are based on chemical reactions, mainly because no further chemical reagents are necessary for the liberation of oxygen. The heat supply can be provided by solar radiation; mare and highland materials may be used and no feedstock beneficiation is necessary for this process (ESA 1996). Further experimental work has to be carried out though, particularly for the condensation step. Overall, the pyrolysis process is very interesting due to its capacity of providing oxygen by a simple reaction without additional reagents.

Martian ISRU concepts

There are three well known processes aimed at the production of propellants and life support consumables from the martian atmosphere (Singh & Shridar, 1998):

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- solid oxide electrolysis
- Sabatier process
- Reverse water gas shift process (Figure 5.3).

Due to the nature of the chemical processes involved, different reaction temperatures and quantities of reagents are required. Only the production of oxygen by solid oxide electrolysis can be performed without reagents.

Solid oxide electrolysis (at ≈1200°C). Oxygen can be produced from CO_2 by solid oxide electrolysis, using a ceramic membrane as an oxygen ion (O^{2-}) conductor at about 1200°C. A crystalline Yttrium-stabilised ZrO_2 membrane is covered with porous platinum electrodes (solid "sandwich" electrolysis cells). The decomposition of CO_2 in the gas phase is described by the following reaction:

$$CO_2 + 238\ \text{kJ/mol} \xleftrightarrow{1200°C} CO + 1/2\ O_2 \qquad (5.5\text{-}12)$$

Initially, CO_2 is decomposed in the gas phase next to the cathode. Then, oxygen is reduced at the cathode and oxygen ions penetrate through the porous platinum into the ceramic oxygen conductor. Transport of negative oxygen ions (O^{2-}) through this membrane occurs as ion migration in the electrostatic field towards the anode. For each oxygen ion penetrating into the ceramic membrane and filling a vacant grid point of the crystal, one oxygen ion is liberated at the anode, thus releasing its electrons. The CO_2 conversion can be performed continuously, but the reaction proceeds only slowly. The separation of oxygen from CO_2 by solid oxide electrolysis is already an established process and similar technology is well established for hydrogen/oxygen-fuel cells.

Sabatier process/water electrolysis (at ≈250°C). The conversion of CO_2 into methane and water using an excess of hydrogen (Sabatier & Senderens, 1902) is known from several industrial applications. In detail the reaction steps are:

Step 1: Reduction of CO_2 using excess hydrogen

$$CO_2 + 4\ H_2 \xrightarrow[\text{vanadium}]{250°C} CH_4 + 2\ H_2O \qquad (5.5\text{-}13)$$

Step 2: Water electrolysis and hydrogen recovery

$$2\ H_2O \xrightarrow{\text{electroysis}} 2\ H_2 + O_2 \qquad (5.5\text{-}14)$$

The main products of reaction (5.5-13) are water (steam) and methane. In a second step, molecular oxygen is produced and hydrogen is recovered by water electrolysis. There is a further need to supply hydrogen, because 50% of the hydrogen remains bound in methane.

Reverse water gas shift process (at ≈400°C to 800°C). The reduction of CO_2 using equimolar quantities of hydrogen leads to the formation of carbon monoxide and water that can be electrolysed for oxygen release and hydrogen recovery. This equilibrium reaction is frequently used in industrial applications for steel production. The reaction steps are as follows:

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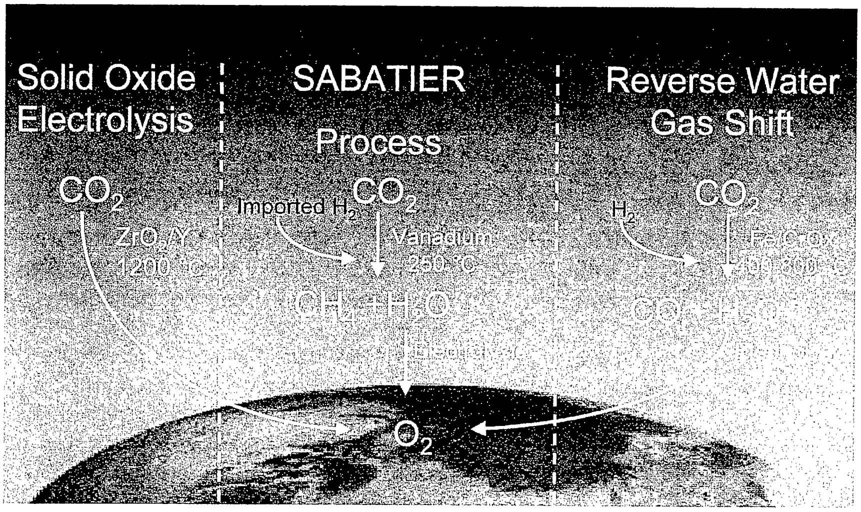

Figure 5.3: Production of propellant and Life Support consumables on Mars.

Step 1: Reduction of CO_2 using hydrogen (equimolar)

$$41.2\ \text{kJ/mol} + CO_2 + H_2 \xleftrightarrow[\text{}]{400\text{-}800°C/\ Fe/CrO_x\text{ - catalyst}} CO + H_2O \quad (5.5\text{-}15)$$

Step 2: Water electrolysis and hydrogen recovery

$$H_2O \xrightarrow{\text{electroysis}} H_2 + 1/2\ O_2 \quad (5.5\text{-}16)$$

The conversion equilibrium of reaction (5.5-15) is forced to the right as the temperature increases, because the reaction is exothermic. Below 830°C CO is the better reducing agent, whereas hydrogen is more efficient at temperatures above 830°C. Therefore reaction temperatures below 800 °C allow only a low rate of conversion. This process cycle is entirely closed with respect to hydrogen ("infinite oxygen machine").

5.5.4 Recommended research and development

Concerning the technical feasibility of the four most promising processes of lunar oxygen production described above it can be stated that:

- the processing steps have, so far, only been verified in laboratory experiments on a small scale;
- a final selection of the most promising concept cannot yet be made;
- up-scaling and closed loop processing are still to be demonstrated (in terrestrial and lunar environments); and
- details of recycling rates and terrestrial re-supply rates are still unclear.

Lunar oxygen production may be different for the "pioneering" period and a later period of "permanent human presence" (Figure 5.4). During the "pioneering" period oxygen would be produced by processes that are easiest to employ (e.g. by ilmenite/glass reduction or carbothermal reduction), but the oxygen yields would be

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relatively low. During the later period of "permanent human presence" oxygen could 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. On-site oxygen production, for life support, on the Moon should be considered in combination with propellant production, due to the complexity of the processes and plant masses involved (see discussion below). This implies that only the production and utilisation of large quantities of oxygen – on the order of 100 tons or more per year – will provide economic advantages (ESA, 1999b).

Concerning the technical feasibility of the ISRU processes on Mars, the following conclusions can be drawn and recommendations made:

- most of the processing steps have been verified in (small scale) laboratory experiments, but further studies are required;
- solid oxide electrolysis as a standalone process is interesting for life support, but less so for propellant production because the reaction of CO + 1/2 O_2 is energetically insufficient for most propulsion purposes on Mars. It should be used as an "O_2 machine" in combination with other processes/propellants;
- reverse water gas shift is a high temperature process that can possibly be used in combination with the Sabatier process;
- the Sabatier process is an established technology for life-support. On Mars it could be used to generate 4.5 tons of H_2O from the atmospheric CO_2 (with 1 ton imported H_2) (or 9 tons of H_2O if methane is pyrolysed for hydrogen recycling) or 8 tons of O_2 (if hydrogen is fully recycled it would even be an "infinite oxygen machine"). Used for propellant production, about 18 tons of CH_4/O_2 mix (optimum ratio 1/3.5) can be generated with 1 ton of imported H_2, if combined with a separate O_2 production;
- a final selection of the most promising concept is not yet possible (eventually a mix of different processes may be the most economical);
- further experimental work is needed;

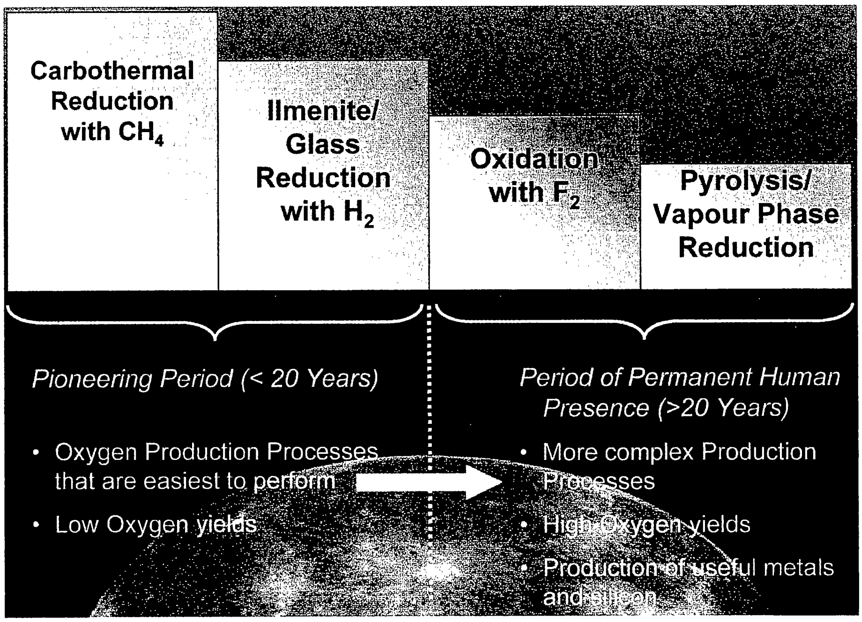

Figure 5.4: Oxygen processing concepts on the Moon

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- up-scaling and closed loop processing are still to be demonstrated (in terrestrial and martian environments!);
- all processing concepts make high demands on power (including heat removal);
- nuclear power supply is desirable because solar energy systems with night time storage are not expected to be efficient for this purpose;
- a propulsion system must be developed which uses CH_4 and O_2;
- technology needs to be developed for the long-term storage of cryogenic propellants during Mars missions and on the surface of Mars.

In conclusion, the economic benefits of lunar oxygen production strongly depend on its use within a long-term lunar base scenario. In addition, valuable by-products can be obtained, e.g. different metals as construction materials or silicon for solar array production. Unless launch costs decrease dramatically in the future, an economic benefit can be expected from the on-site production of lunar oxygen. These estimates presume a 20-year lifetime of the production plant.

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 (ESA, 1999b). 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 might be included. Furthermore, the utilisation 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.

All discussed processing options have to be investigated experimentally in more detail in order to make a decision on a preferred concept or a combination of concepts. Significant upscaling of terrestrial laboratory processes is necessary, considering also lunar and martian environmental constraints. In addition, the technologies must be developed for power supplies, cryo-storage, heat removal and especially the handling of large amounts of regolith.

5.6 Recommended ECLSS for the three human exploratory mission scenarios

ECLSS functions and techniques are not yet sufficiently developed to meet the requirements of human exploratory missions. Investigations are required into advanced life support system technologies based on bioregenerative technologies, supplementary physico-chemical technologies and natural resource utilisation, complemented 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. An ECLSS should be developed for each mission scenario.

Scenario 1: Outpost at the lunar south pole
Earth-Moon-Earth transfer: With regard to the human needs of Mission Scenario 1 (Table 3.3), the vehicle(s) required for the transfer from Earth to the Moon and back to Earth (only 3 to 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.

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Lunar base: If the lunar base is foreseen as a permanently equipped and inhabited set-up and not only for a single 180 day mission, the ECLSS of the base must be able to operate continuously without shutdown and restart when a new crew arrives. This makes high demands on the long-term stability and reliability of all systems. From the mass figures in Table 3.3, it can be deduced that it is advantageous to close the ECLSS loops to the greatest extent possible with regard to the atmosphere and, even more importantly, with regard to water, even though the regular transport capacity would allow to replace quite a high proportion of consumables.

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

- In a first step, the efforts should focus on the recycling of the atmosphere and of water, which comprise about 90% of the mass of consumables for a 180 day mission.
- Initially, the ECLSS should start with conventional physico-chemical techniques, which will be replaced in steps by bioregenerative methods. The physico chemical systems should remain as redundant elements.
- The biological components most adapted to these functions are as follows:
  - algae as oxygen producers and CO_2 consumers for the management of the atmosphere;
  - biological water treatment systems (e.g., treatment of crew waste by bacteria and perhaps fungi) as a first step for the water regeneration/production, followed by 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 day Mars mission

Looking at the enormous human needs for a mission to Mars (Table 3.4) it becomes clear that the transfer vehicle(s), as well as the outpost station, should be equipped with ECLSS 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 maximise the use of the natural resources of the planet. 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 two members remaining in Mars orbit and four landing on the surface, it is necessary to develop two autonomous life support systems, which could work together during the transfer phases.

Earth-Mars and Mars-Earth transfer: During the trip to Mars and back to Earth, the life support system must be able to sustain a crew of six; in addition this is required for the crew of two remaining in Mars orbit. The system must, at least, be able to recycle the atmosphere and water, thereby reducing the mass of

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consumables by 90%. The most probable biological systems involved are algae and microbial reactors, 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 quickly (2 to 3 days) after failure.

Higher plants could be used, depending on the area available (it must be realised that an area of about 15 m^2 is the minimum requirement for a monoculture needed for feeding one person, but that this would probably extend to an area of 30 to 40 m^2). In the spacecraft, higher plants would be introduced only as sources of fresh food, to complement the diet (up to 20-30%). A BLSS could then recycle virtually all of the oxygen and water and provide 30 – 40% of the food (including higher plants and algae as a complement to the diet). This would reduce the mass of consumables to about 6000 kg (mainly food) for the whole transfer mission (Table 3.4), but the instrumentation (chamber, probe, energy supply) masses are not included in the calculations. The use of a cargo launched before the Mars mission could reduce the mass to 3000 kg (for each transfer phase).

1000 day Mars outpost station: The 525 day stay on Mars, with nearly Earth-like day/night cycles, makes it desirable to develop bioregenerative technologies and physico-chemical ECLS components which are mutually supportive, in particular with regard to water recycling and on-site food production. The required consumables for the return mission from Mars to Earth may be produced in the Mars station by biological and 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 from the beginning of the mission. In this case it only requires two thirds 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 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....).
  - 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 plants for food production (plants or seeds coming from the spacecraft and planted on Mars).

Scenario 3: 500 day Mars mission

Whereas during the transfer phase, the requirements on the ECLSS are similar to those for Scenario 2, in this case the four crew members stay only 30 days on the surface of Mars. Therefore, during the transfer phase, the life support system can be similar to that in Scenario 2. From the mass figures in Table 3.4 it can be concluded that the ECLSS of the transfer vehicle must be capable of maintaining a comfortable environment for six crew members throughout the transfer mission time of 410 days, and for two crew members throughout the orbiting period of 30 days. Consequently, the transfer vehicle's ECLSS must be closed to a high extent concerning oxygen/carbon dioxide recycling and water/waste recycling.

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The stay time on Mars is rather short, so that the decision whether to use an ECLSS with a high degree of loop closure (technically complicated) or to provide a simple, robust, ECLSS working mainly with consumables, needs to be evaluated in more detail. This cannot be done in the frame of this study.

In particular, the size/capacity of an electrical power production plant on the surface of Mars drives the design of an appropriate ECLSS. As a first estimate it is thought that a simple non-regenerative ECLSS has more advantages (simple, very mature technology available, reliable, etc.) than disadvantages (higher overall mass) over a regenerative ECLSS.

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6 Suitability of Existing Facilities and Technologies as Testbeds for Human Exploratory Missions

6.1 Existing terrestrial analogues, ISS and precursor missions as test beds for risk assessments of interplanetary and planetary environments

The currently used terrestrial analogues which that are suitable test beds for assessing the risks of interplanetary and planetary exploratory missions are as follows:

- Isolation -- Confined environment simulation (IC). These environments are either specifically created within confinement chambers, or are available as naturally existing confinements, such as Antarctic bases (ANT), submarines, or off-shore platforms. They are especially suited for long-duration studies.
- Bed-Rest (BR) for simulating microgravity effects. Different versions have been used, with or without head-down tilt, or head-up tilt. They are generally used for studies of microgravity effects on healthy subjects, with regard to cardiovascular deconditioning, exercise capacity impairment, and musculo-skeletal disorders (Nicogossian, 1994; Pavy Le Traon et al. 1997). This analogue can also be used for long duration studies.
- Patient Imobilisation (PI). Some particular situations, such as long term patient immobilisation (with spine trauma for example), have also been used for studying cardiovascular deconditioning, exercise capacity impairment, and musculo-skeletal disorders (Daphtary et al., 2000).
- Water Immersion (WI): Simulation of microgravity using water immersion has been used to study rapid and transitory fluid and hormonal regulation. The normal duration of WI is limited to a maximum of 12 to 24 hours (Stadeager, 1992).
- So-called Water "Dry" Immersion (WDI). This simulation procedure has the advantage that it can be used over longer periods of time than WI, It has been mainly been used to study cardiovascular deconditioning as well as body fluid and mineral changes (Leach-Huntoon et al., 1998).
- Parabolic flight (PF). PF allows short-term exposure to microgravity of 25-30 s maximum. Such short-term simulations of microgravity are suitable for studies of acute phenomena, such as cardio-vascular and neuro-sensory phenomena (Nicogossian, 1994) as well as for the demonstration, testing and utilisation of technical equipment under microgravity. In this case, in addition to studies on humans, animals, tissue or cell studies are also possible.
- Sounding rockets (SR). SR and drop towers provide microgravity conditions for very short periods. They have been used for cell studies and for technical demonstrations (Moore & Cogoli, 1996).
- Life Support Breadboards (LSB). Breadboards are widely used for studies related to advanced life support systems. Large scale breadboards, such as Habitable Closed Chambers (HCC) are required when humans are involved, even for very long duration simulations, e.g., in IC.
- Ionising particle accelerators (IPA). Heavy ion accelerators have been used for studying the biological effects of radiation at the cell level and also at the body level by using animal models (Kiefer et al., 1996).

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- Altitude Chambers (AC). These facilities have been especially used for optimising EVA exercise scheduling (Powell et al., 1994).
- Mathematical modelling and computer simulations, which will be dealt with in more detail in Section 6.2.

The International Space Station (ISS) will provide an ideal opportunity for studying the combined effects of many aspects of the space environment over long periods of time. The Station's design as a permanent laboratory in microgravity conditions will provide scientists with an ideal test bed for studies of the effects on humans of the environmental conditions likely to be encountered during interplanetary travel. The possibility of using devices capable of simulating reduced gravity (e.g., a large-scale centrifuge) will also provide an opportunity to study the effects of reduced gravity to be encountered on the lunar and martian surfaces (0.16 g and 0.38 g respectively) (Krettenberg et al., 1998; Greenleaf et al., 1996; Yajima et al., 2000; Simonson et al., 2000; Young et al., 2000). It is a further advantage of the ISS that it can be used for studies on humans, animals, tissues and cell cultures.

As precursor missions (PM), automated robotic exploratory missions to the moon and to Mars are considered to be ideal opportunities for studying the interplanetary and planetary environments, especially their radiation fields, and to evaluate the systems for In-Situ Resources Utilisation (ISRU).

6.2 The Integrated Performance Modelling Environment

It is important that proper system engineering principles are applied at all stages during the development of a new system. An essential component of system design and development is the use of modelling and simulation, so that key system parameters can be adjusted and fundamental problems in the system design can be identified and corrected at the earliest possible stage. These principles apply both when developing a new system from scratch and when using an existing design for a new set of missions. If the mission under consideration depends critically on the contribution of the human crew, it is important that any simulation of the mission includes simulation of the human element. The application of an integrated modelling framework at an early stage in the planning of exploratory missions can then be used both to identify potentially important stressors that bear on operational problems, and to highlight the need for research into the effects, if they are likely to be crucial. Early modelling analysis can also contribute to the development of specific aspects of an experimental programme.

6.2.1 The human component

It has to be acknowledged at the outset that the human element of the system is different in kind from the other system components. The "mechanical" or "electronic" components of a large system tend to behave in a predictable manner in an engineering sense, and will be designed to stay within pre-defined operating limits when the external environmental conditions meet the specified standard. The human element is, however, different. There is intrinsic variability in the performance of individuals within a team and between individuals within the same team. Although individuals undertaking a demanding mission will be trained to a specified level of skill at the task they will be required to undertake, this will not remove all sources of variability between individuals. Similarly, an individual's performance and behaviour are subject to modification by the external

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environment. To provide a basis for the discussion of the modelling of the human element it is useful to define "performance" and "behaviour" in a slightly more precise manner.

Behaviour: For the purposes of modelling, the analysis of behaviour is defined as the analysis of what a team member is likely to do in a given context. At its most complex, the description of behaviour can become open-ended and it is then very difficult to define an appropriate simulation mechanism. However, if the overall mission is composed of activities for which the crew is well-trained, then it is frequently reasonable to assume that behaviour will lie within well defined limits.

Performance: For the purposes of modelling, performance is defined as how well a particular task is executed, given that a particular course of action has been chosen. Metrics of performance are usually speed and accuracy – i.e. how quickly a task is performed and whether errors are made. Human performance has been investigated systematically in a wide range of contexts over the last 100 years, and there are many data on performance of a wide range of tasks.

6.2.2 Approaches to modelling

A number of approaches have been developed to modelling the performance of small teams in the military context. The most important and widely applied are task network modelling and rule-based cognitive modelling. Both approaches have advantages and disadvantages and these are summarised in the following.

Task network modelling: The most widely applied and technically developed method for modelling small team behaviour is the use of task network modelling. In this approach the behaviour of the team is broken down, using hierarchical task analysis, into a series of atomic behaviours at the level appropriate to the current requirement. The interactions between team members are described as task elements representing communication between team members. Task interdependencies describe co-ordination and backup behaviour is represented through the application of appropriate simple algorithms. The approach lends itself to the capture of those elements of system behaviour that are a strong function of timeliness and task interdependency, but provides no assistance in the areas that depend strongly on cognitive behaviour. In this approach, one of the standard methods of describing the interaction between an individual operator and a system is merely extended to describe the interactions between a set of operators and a common system, by representing the team interactions as explicit tasks.

Rule based cognitive modelling: In the same way, the rule-based approaches to individual behaviour have themselves been extended to represent small groups. These approaches make a real attempt to describe or even emulate the cognitive processes that the individuals within a team have to go through to reach decisions on their actions. This approach tacitly assumes that time is not the key element in the performance of the relevant task, but that the information content of the environment is critical. It is assumed that overall behaviour is dominated by the cognitive elements rather than by the more mechanistic and time dependent elements of the team task.

The choice between these approaches is a function, as in all modelling problems, of which aspect of the system under consideration dominates system behaviour. If timely action by team members that depends on co-ordination and communication is the key element in the problem, then task network modelling

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is likely to provide a good approach. This is normally the situation for the trained response to specific mission contexts. If the key element in the problem is to establish whether the overall team behaviour leads to good or to bad decisions, and timeliness is not a prerequisite, then the more expensive cognitive modelling approach is likely to be appropriate. For the modelling of system performance in a well-defined human space mission, task network modelling is the most promising approach.

6.2.3 Mission stages to be modelled

A key step in the analysis of a mission is the selection of the appropriate stages for simulation. In the context of a very long and complex mission, it is appropriate that a small subset of critical mission sequences should be selected for simulation. Before the mission stages can be selected it is necessary to establish the criteria on which an appropriate choice can be made. It is important to study two classes of potential mission event that are critical to mission success:

- mission emergencies, and
- critical mission phases during which crew performance is under extreme stress.

It is assumed that a task-based approach to the simulation will be adopted. The first step in the modelling is to define which tasks will be performed by the crew, and which by the system, during the critical mission phases. From the definition of the tasks, the appropriate human or system performance can be assigned to each task and the overall logic flow established.

Effects of stressors: The effect of almost all environmental stressors is mediated by the subject state, and the subject state is determined by a combination of the environmental state and the subject traits. The general effects of stressors are illustrated in Figure 6.1. Workload – task demand – is a distinct stressor that has an overall effect on task performance that is not mediated by an intermediate state. If task demand is high, there is a variety of possible task degradations, including a simple increase in the time taken to perform a task, increase in errors in the task performance and the shedding of lower priority tasks.

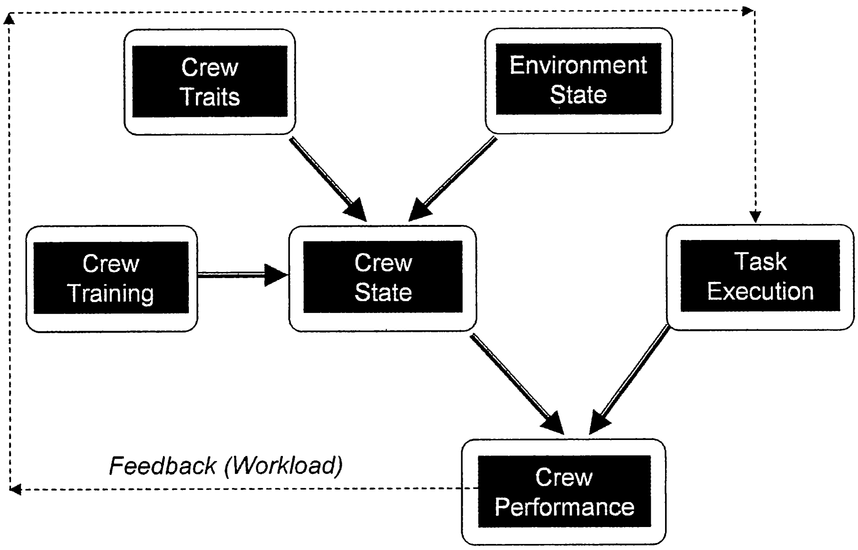

Figure 6.1: The effect of environmental stress on task performance

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The stressors that should be considered as a priority in the analysis of human space flight are listed in Table 6.1. To provide a satisfactory model of the effects of the stressor on task performance, it is necessary to be able to model both the effect of the environmental stressor on subject state and the effect of subject state on task performance and/or behaviour. The critical stressors fall into three groups, (i) those that have already been modelled systematically, (ii) those that are the subject of current research and (iii) those that are not yet the subject of investigation.

Table 6.1: Key stressors in manned spaceflight – and the current state of knowledge

Stressor	Model source Stressor to state	Model source State to performance
Anxiety	Not available	Not available
Sleep loss/Circadian	CHS/DLR Alertness model	IPME project findings
Thermal effects	Texas model/CHS 2-D Thermal model	IPME project findings
Reduced gravity - General effects	Not available	Not available
Reduced gravity - Loss of bone calcium	Not available currently	Not available currently
Radiation	NATO sources to be confirmed	NATO sources to be confirmed
Background noise	General effects available in the literature Fatigue effects need to be examined (indirect effects on sleep have been investigated)	General effects available in the literature Indirect fatigue effects need to be examined
Space sickness	Terrestial analogue – motion sickness – effects in the general literature need to be systematised. Data from literature on space sickness that can be systematised.	Terrestial analogue – motion sickness – effects in the general literature need to be systematised. Spaceflight data can be reviewed if there is task data available
Task demand/workload		A range of models in the general literature. IPME project findings
Team stresses	Under active research TNO, DCIEM, NAWC TSD, DERA	Under active research TNO, DCIEM, NAWC TSD, DERA
Monotony and boredom	No general model currently available. There is a substantial general literature on the effects, that should be suitable assuming that 'arousal' is the state.	No general model currently available. There is a substantial literature relating 'arousal' to task performance.
Crowding	No general model available Intervening state unknown. Review relation with State Anxiety	Depends on identified state
Lack of privacy	No general model available Intervening states unknown. Review relation with State Anxiety and team stressors	Depends on identified state
Confinement/isolation	No general model available. Literature on isolation studies available. Intervening state would need review	Depends on identified state

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If the critical phases of e.g., a human mission to Mars are to be simulated satisfactorily, it will be necessary to fill in the gaps identified in Table 6.1. The key gaps are:

- the short term and long term effects of reduced gravity,
- confirmation that results relevant to motion sickness apply to space sickness, and
- team stressors and anxiety, and the related stresses of crowding, lack of privacy, confinement and isolation.

6.2.4 Integrating the human and system models

A general framework in which the full system can be modelled – including both system and human elements – has a number of requirements:

- It must support the representation of human states
- It must support the representation of the relationship between human state and human performance
- It must support the representation of the relationship between the environment and the human state
- It must support a model of the effect of task demand
- It must provide a simple way of describing tasks and the general behaviour of the system

The relationship between environment and state has, in the past, been modelled through complex physiological models, in the form of free-standing software. It is cost effective to seek re-use of these existing models through the use of a modular architecture rather than through the construction of a special special-purpose single model for manned spaceflight.

The Integrated Performance Modelling Environment (IPME) has been developed jointly by the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) and the United Kingdom Defence Evaluation and Research Agency (DERA). It is a task network modelling tool based on the Micro Saint discrete event simulation engine. It provides explicit support to the Environment/State/Performance model described previously. It provides support to a modular architecture in which complex models of external processes can be connected to the framework through UNIX sockets.

It is recommended that the task network approach employed in the IPME be adapted to the simulation of the critical phases of the flight. The complex effects of the stressors referenced in Table 6.1. should be established for the conditions anticipated in the three mission scenarios. The critical phases of the missions should be identified and the relevant task analysis undertaken. The modelling framework should be developed in a modular manner so that pre-existing models can be employed in a cost effective way. Simulations campaigns should be good opportunities to improve and validate the IPME.

6.3 Terrestrial Analogues and the ISS as test beds for addressing medical and physiological crew health control issues

Table 6.2 lists the crew health control issues, together with possible utilisation of terrestrial analogues and the ISS as test beds for facilitating their resolution. The studies of health risk assessment may concern humans, but some of them can also be performed on animals, living tissue or cell cultures.

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Table 6.2: Crew health control issues for exploratory planetary missions, and possible utilisation of terrestrial analogues as test beds.

Medical Physiological issues/simulation means	LAB	BR	PI	WI/WDI	PF	IC	AE	HCC LSB	AC	SR	IPA	ISS-0g	ISS-Rg	PM
Design compact equipment for long term spaceflight allowing: The identification of pathogenic micro-organisms The determination of the in vitro Minimum Concentration of Inhibition of antibacterial, antibiotic, antifungal, and antiparasitic agents Blood cell counting and analysis Blood and urine chemical analysis Blood or urine biomarkers for identification and quantification of potential endocrine, nutritional, and metabolic disorders, and to monitor bone and muscle metabolism.	-	-	-	-	+/-	+	-	-	-	-	-	++	-	-
Ensure that compact abdominal ultrasound, endoscopy and X-ray equipment will be available onboard the Mars transit vehicle (for the 500 and 1000 day Mars missions), and the Mars habitat (for the 1000 day Mars mission).	-	-	-	-	+/-	+	-	-	-	-	-	++	-	-
Design optimised exerciser regimens for long duration space flight.	-	++	+	-	+	+/-	-	-	-	-	-	++	+	-
Design a medical kit for long term space flight.	-	-	-	-	+/-	+	-	-	-	-	-	++	-	-

Rating: "++" = mandatory, "+"= useful, "+/-"= can be used with uncertainties, "-"= not relevant

(Cont'd)

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Table 6.2 (Cont'd)

Medical Physiological issues/simulation means	LAB	BR	PI	WI/WDI	PF	IC	AE	HCC LSB	AC	SR	IPA	ISS-0g	ISS-Rg	PM
The onboard equipment (diagnostic and therapeutic) should be sufficient to treat common dental, eye and ENT diseases.														
Design medical equipment for exploratory long term space flight, to include:	-	-	+/-	-	+/-	+	-	-	-	-	-	++	-	-
pulmonary life support equipment (with hyperbaric capability) to be used in case of decompression sickness														
Anaesthesia														
Resuscitation														
Endoscopical surgery														
Surgical sets adapted for 0g use														
Immobilisation														
Medical equipment to manage adverse effects of reduced temperature, heat and light exposure should be available onboard the Mars transit vehicle (for the 500 and 1000 day Mars missions), and Mars habitat (for the 1000 day Mars mission)	-	-	-	-	+/-	-	-	-	+	-	-	+	-	-

(LAB = ground laboratory, BR = Bed Rest simulations, PI = Patient immobilisation, WI = Water Immersion/WDI = Water "Dry" Immersion, PF = Parabolic Flight, IC = Isolation – confinement simulations, AE = Antartica/underwater/off-shore situations, HCC= Habitable Closed Chamber / LSB= Life Support Breadboards, AC = Altitude Chamber, SR = Sounding rocket, IPA = Ionising Particle Accelerator, ISS 0g = International Space Station under 0 gravity, ISS Rg = International Space Station under Reduced gravity, PM = Precursor Missions)

Rating: "++" = mandatory, "+"= useful, "+/-"= can be used with uncertainties, "-"= not relevant.

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Hence, in the field of the medical and physiological crew health issues, flight opportunities on the ISS, Isolation – confinement simulations, Bed Rest simulations and, for some issues Patient Immobilisation, will offer ideal opportunities to progress in the health risk assessments for interplanetary and planetary human exploratory missions.

6.4 Terrestrial Analogues and ISS as test beds for addressing psychological crew issues

A number of necessary topics for fundamental research and development of countermeasures for addressing psychological crew issues during the three mission scenarios are listed in Table 6.3.

In summary, in the field of psychological issues: flight opportunities on the ISS; analogue environments, such as Antarctica, underwater habitats, or off-shore platforms; isolation chambers; habitable closed chambers equipped with life-support systems (including hyperbaric and altitude chambers) and bed rest simulations, will provide ideal opportunities to progress in the assessment of psychological risks for interplanetary and planetary human exploratory missions.

6.5 Terrestrial, ISS and precursor missions as test beds for addressing radiation crew risk control issues

The research studies in the field of radiation risk assessment may involve humans, animals, living tissue and cell cultures. Table 6.4 lists relevant radiation exposure issues, together with possible utilisation of terrestrial analogues and ISS as test beds for facilitating their resolution.

The ISS, ionising particle accelerator experiments and Mars precursor robotic missions will be provide ideal opportunities for crew radiation risk assessment for human interplanetary and planetary exploratory missions. Some 'non-standard' terrestrial facilities, which should, more accurately, be included within the IPA (Ionising Particle Accelerator) category, will be necessary for conducting research and development required for space radiation countermeasures. They are the following:

- Heavy ion accelerators (HIAC)
- Microbeam irradiation facilities (MBF)
- Experimental animal maintenance (EAM)
- Human exposure facilities (HEF)

HIAC: 'Normal' heavy ion accelerators with appropriate energy and charge capabilities are needed for the development/validation of dosimetric equipment. Standard radiobiological experiments on such accelerators will only yield fundamental 'background' information regarding the required dose response function for mammalian/human radiogenic carcinogenesis.
MBF: Relevant quantitative data on mammalian/human radiogenic carcinogenesis corresponding to the particle fluxes in space can only be obtained from irradiation experiments with single/few charged particles. A number of microbeam facilities have been constructed or are under construction for that purpose.

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Table 6.3: Evaluation of utilisation of terrestrial analogues and ISS as test beds for psychological research and development.

Medical Psychological issues / simulation means	LAB	BR	PI	WI/WDI	PF	IC	AE	HCC	AC	SR LSB	IPA	ISS-0g	ISS-Rg	PM
Psy01: Cognitive and Psychomotor Performance														
01.1: Effects of hypogravity, confinement and isolation on cognitive and psychomotor performance	–	+/-	–	–	+/-	++	+	+	–	–	–	++	–	–
01.2: Acquisition of new perceptual-motor skills	–	–	–	–	–	++	+	+	–	–	–	++	–	–
01.3: Effects of workload transition	–	+/-	–	–	–	+	+	+	–	–	–	+	–	–
01.4: Effects of EVA	–	–	–	–	–	–	–	–	+	–	–	++	–	–
01.5: Effects of artificial gravity	–	–	–	–	–	–	–	+	–	–	–	++	+	–
Psy02: Maladaptive Individual Reactions														
02.1: Effects of hypogravity, confinement and isolation on sleep quantity and quality	–	+/-	–	–	–	++	++	+	–	–	–	++	–	–
02.2: Effects of weakened diurnal *zeitgebers* in space and on the Moon on circadian-rhythms	–	+/-	–	–	–	++	++	+	–	–	–	++	–	–
02.3: Effects of confinement and isolation on mood and mental/behavioural–health	–	–	–	–	–	++	++	+	–	–	–	+	–	–
02.4: Individual characteristics which predict for optimum adjustment	–	–	–	–	–	++	++	+	–	–	–	+/- [1]	–	–
02.5: Long-term dependence on life-support systems	–	–	–	–	–	–	+/-	++	–	–	–	+	–	–
02.6: Efficacy of individual coping strategies	–	–	–	–	–	++	++	+	–	–	–	+	–	–
Psy03: Interpersonal Issues														
03.1: Effects of confinement and isolation on crew interactions	–	–	–	–	–	++	+	+	–	–	–	+	–	–
03.2: Interpersonal compatibility and crew composition	–	–	–	–	–	++	+/-	+	–	–	–	+/-[1]	–	–
03.3: Effects of confinement and isolation on crew communication with the outside	–	–	–	–	–	++	+	+	–	–	–	+	–	–
03.4: Individual characteristics which predict for optimum interpersonal behaviour	–	–	–	–	–	++	+	+	–	–	–	+/- [1]	–	–
Psy04: Psychological Countermeasures														
04.1: Define functional (size) requirements for individual crew quarters[2]	–	–	–	–	–	+	–	+	–	–	–	+	–	–
04.2: Investigate interior decor preferences	–	–	–	–	–	++	+	+	–	–	–	+	–	–
04.3: "Adjustable autonomy" as concept for designing autonomous systems[2]	–	–	–	–	–	+	+	+	–	–	–	+	–	–
04.4: Methods for filling low workload periods with meaningful tasks				**— Not applicable because of dependence on specific mission characteristics —**										

Scoring: ++ = mandatory, + = useful, +/- = can be used but uncertainties remain, - = not relevant

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Table 6.3 (Cont'd):

Medical Psychological issues / simulation means	**LAB**	**BR**	**PI**	**WI/WDI**	**PF**	**IC**	**AE**	**HCC**	**AC**	**SR LSB**	**IPA**	**ISS-0g**	**ISS-Rg**	**PM**
04.5: Methods for maintaining good sleep and stability of circadian-rhythms	–	+/-	–	–	–	++	+	+	–	–	–	++	–	–
04.6: Development of psychological screening and selection tools	–	–	–	–	–	++	+	+	–	–	–	++	–	–
04.7: Guidelines for psychological crew composition and development of assessment tools	–	–	–	–	–	++	+/-	+	–	–	–	-[3]	–	–
04.8: Development of training for space-crew	–	–	–	–	–	++	+	+	–	–	–	++	–	–
04.9: Development of training for ground-crew	–	–	–	–	–	++	+	+	–	–	–	++	–	–
04.10: Development of leadership training for commander	–	–	–	–	–	++	+	+	–	–	–	++	–	–
04.11: Development of training for autonomous treatment of psychiatric disorders				**— Not applicable because of generally low incidents rates of psychiatric disorders —**										
04.12: Development of methods suitable for remote monitoring of crew behaviour and performance	–	–	–	–	–	++	+	+	–	–	–	+	–	–
04.13: Development of on-board training tools for retention of perceptual motor skills	–	–	–	–	–	+	+	+	–	–	–	++	–	–
04.14: Development of methods for providing additional sensory stimulation	–	+/-	–	–	–	++	+	+	–	–	–	+	–	–
04.15: Design of optimised tools for supporting recreational activities in space	–	–	–	–	–	+/-	+/-	+	–	–	–	++	–	–
04.16: Development of technologies for electronic uplink of news & entertainment supplies[2]	–	–	–	–	–	+	+	+	–	–	–	+	–	–
04.17: Development and testing of new technologies for crew-ground communication	–	–	–	–	–	++	+	+	–	–	–	+	–	–
04.18: Methods of contraception in space	–	–	–	–	–	–	–	+	–	–	–	++	–	–
04.19: Definition and design of psychiatric components of crew-health facility	–	–	–	–	–	–	–	+	–	–	–	++	–	–
Integrated Performance Modelling Environment	+	+/-	–	–	+	++	+	++	+	–	–	++	++	–

[1]Research difficult because of restricted number of subjects available
[2]Most of the research needed can be done in laboratory
[3]Dependent on policy of ISS crew composition (currently no compatibility assessment implemented)

(LAB = ground laboratory, BR = Bed Rest simulations, PI = Patent immobilisation, WI = Water Immersion/WDI = Water "Dry" Immersion, PF = Parabolic Flight, IC = Isolation – confinement situations, AE = Antartica/underwater/off-shore situations, HCC = Habitable Closed Chamber/LSB = Life Support Breadboards, AC = Altitude Chamber, SR = Sounding rocket, IPA = Ionising Particle Accelerator, ISS 0g - International Space Station under 0 gravity, ISS Rg = International Space Station under Reduced gravity, PM = Precursor Missions)
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Table 6.4.: Radiation risk assessment for exploratory planetary missions and possible utilisation of terrestrial analogues as test beds.

Radiation exposure issues/simulation means	**LAB**	**BR**	**PI**	**WI /WDI**	**PF**	**IC**	**AE**	**HCC LSB**	**AC**	**SR**	**IPA**	**ISS-0g**	**ISS-Rg**	**PM**
Radiation environment	–	–	–	–	–	–	–	–	–	+	–	++	++	++
Radiation surveillance	–	–	–	–	–	–	–	–	–	–	–	++	++	+
Radiation effects: quality-unique HZE mechanisms	–	–	–	–	–	–	–	–	–	–	++	–	–	+
Radiation effects: quality-single particle effects	–	–	–	–	–	–	–	–	–	–	++	–	–	+
Microgravity interactions: early effects	–	–	–	–	–	–	–	–	–	+/-	–	++	++	+
Microgravity interactions: late effects	–	–	–	–	–	–	–	–	–	+/-	–	++	++	+
Countermeasures	–	–	–	–	–	–	–	–	–	–	+	++	++	+

(LAB = ground laboratory, BR = Bed Rest simulations, PI = Patient immobilisation, WI = Water Immersion/WDI = Water "Dry" Immersion, PF = Parabolic Flight, IC = Isolation – confinement simulations, AE = Antartica/underwater/off-shore situations, HCC= Habitable Closed Chamber / LSB= Life Support Breadboards, AC = Altitude Chamber, SR = Sounding rocket, IPA = Ionising Particle Accelerator, ISS 0g = International Space Station under 0 gravity, ISS Rg = International Space Station under Reduced gravity, PM = Precursor Missions)

Scoring: ++ = mandatory, += useful, +/- = can be used with uncertainties, - = not relevant

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EAM: Since directly usable data can only be obtained with from animal irradiation experiments, such animal maintenance facilities will be required. At many accelerators such equipment exists as part of the standard facilities, so in these cases the terrestrial analogue requirement might be redundant.

HEF: The only research where a human exposure facility will be required concerns the suggested investigations on the effectiveness of dietary intake to control the oxidative status of cells and tissues. The necessary strict control of dietary input and metabolic output makes it difficult to conduct such studies with human volunteers to be undertaken in their normal living environment. Such studies could be combined with other human exposures (bed rest, confinement/seclusion or similar studies). The practicability of such studies and their concrete experimental design will possibly require feasibility studies to be conducted.

6.6 Terrestrial analogues and ISS as test beds for advanced life support issues

Table 6.5 lists the general issues concerning advanced life support and the possible utilisation of the terrestrial analogues and ISS as test beds to assess these issues. It should be noted that almost all the processes which are controlled by life support systems in general, and ALS relevant processes in particular, are slow, which means that potential parameter changes of controlled features need significant periods of time. Exceptions from that statement are rare. With regard to terrestrial analogues this implies that those analogues that provide specific conditions for only short periods of time are not so helpful. A lot of the life support processes (e.g. solid/liquid/gas phase separation wherever it occurs) are affected by gravity conditions To this extent the ISS provides an ideal test platform for most of the ALS processes.

In conclusion, in the field of advanced life support technologies, the ISS, isolation chamber simulations, a habitable closed chamber and the experimental utilisation of life support breadboards and of ground laboratories are mandatory steps to progress in the technological development of advanced life support for interplanetary and planetary human exploratory missions.

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Table 6.5: Advanced life support issues for exploratory planetary missions and possible utilisation of terrestrial analogues as test beds

Advanced Life Support Iissues/simulation means	LAB	BR	PI	WI /WDI	PF	IC	AE	LSB HCC	AC	SR	IPA	ISS-0g
Physico-chemical ALS												
Air loop and oxygen reclamation loop is already realised up to breadboard level, but several issues need to be studied w.r.t. effects on operation and/or performance of reduced- or microgravity	-	-	-	-	-	+	-	n.a.	-	—	-	++
Water recovery/recycling equipment and processes for space application only exist in quite preliminary state in Europe	-	-	-	-	-	++	-	++	-	—	-	++
Waste processing/recycling equipment also only exists in quite preliminary state in Europe	-	-	-	-	-	++	-	++	-	—	-	++
Food production and recycling is not possible by physico-chemical processes	-	-	-	-	n.a.	n.a.	-	n.a.	-	n.a.	-	n.a.
Bioregenerative ALS												
Oxygen production/Carbon dioxide removal	-	-			-	++		++		-		++
Biological waste degradation – a key subsystem for closing the ALS; actually incenerator are the most studied systems	-				-	+		++		-		++
Higher plant culture strategy – the core of most of the BLSS projects; the main method for producing food	-				-	++		+		-		++
Photobioreactor strategy – core of BLSS as oxygen producer/carbon dioxide remover.	-				+	++		+		-		++
Water treatment – most of the mass is water; each biological process can act as a filter	-				-	+		+		-		++
Radiative effects for short and long term – for both micro-organisms and higher plants	-				+	-		+				++
Low and no gravity effects for biological growth. This is also important for exchange processes between phases	-				+	-				-		++
Environmental Monitoring												
Chemical composition/contamination of air, water, surfaces	-				-	++		-		-		++
Spacecraft/habitat microbial fauna	-				-	++		-		-		++
Identification of biomarkers for the control of the state of biological LSS	++				-	+		+		-		++
Identification of biomarkers for the verification of the genetic identity, integrity and stability of biological components of LSS	++				-	+		+		-		++
Natural Resources: tbd												

(LAB = ground laboratory, BR = Bed Rest simulations, PI = Patient immobilisation, WI = Water Immersion/WDI = Water "Dry" Immersion, PF = Parabolic Flight, IC = Isolation – confinement simulations, AE = Antartica/underwater/off-shore situations, HCC= Habitable Closed Chamber / LSB= Life Support Breadboards, AC = Altitude Chamber, SR = Sounding rocket, IPA = Ionising Particle Accelerator, ISS 0g = International Space Station under 0 gravity, ISS Rg = International Space Station under Reduced gragitygravity, PM = Precursor Missions)

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Young L.R., H. Hecht, L. Kenko, C. Lyne C. Cheung, J. Kavelaars, 2000, *Artificial gravity as a countermeasure to prolonged weightlessness*. Abstract Volume of the 13th IAA Humans in Space, Santorini, May 2000, p. 201.

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7 Proposed European Strategy in life sciences and life support systems in preparation for human exploratory missions

7.1 Roadmap for a future European strategy in life sciences related issues towards human exploratory missions

7.1.1 Recommended overall strategy

Human exploratory missions to the Moon or Mars, i.e. beyond Earth orbit, are widely considered as the next logical step after the realisation of the ISS, which is being placed in LEO as a long-term human habitat and laboratory in space. Such missions will only be possible as a global international cooperation venture, involving all spacefaring nations. With the ISS, the first grand international space enterprise involving peaceful cooperation on a global scale has been achieved. If Europe plans to continue this international cooperation in space by becoming an active player in future international human exploratory missions, it should prepare in time. Europe has achieved a competitive position in space life sciences, particularly in fields such as human physiology and countermeasures, gravity biology, and radiation biology and dosimetry. From previous human missions in LEO, e.g., on board Spacelab and Mir it has also gained experience in life support technologies. Lessons learned from the experience gained on the ISS may help Europe to increase its responsibility and visibility in future large international space projects. However, as recently stated in the ESSC-ESF-assessment of the new ELIPS programme, this bonus can easily be endangered, if Europe does not continue and enlarge its research opportunities in support of the life sciences and life support activities mentioned above.

In order to play an active part in future human exploratory missions with regards to human health issues, it is recommended that ESA set up a research and development strategy that aims at:

- fostering those fields in life sciences and life support technology where Europe has reached a competitive and leading role and
- strengthening the competitiveness of European science and industry by a stronger coordination of space activities with terrestrial activities at regional and European level.

Several approaches can be considered for fundamental research in human health issues, countermeasures and life support systems developments, including but not limited to:

- research during long-duration orbital spaceflight, with emphasis on the ISS or other human missions in LEO;
- research on robotic precursor missions to the Moon and Mars, including orbiters and landers;
- research during ground-based simulation studies using terrestrial testbeds, isolation chambers (including altitude and hyperbaric chambers equipped with life-support systems), or heavy ion accelerators;
- research in appropriate analogue natural environments like Antarctica or undersea habitats, in cooperation with national organisations responsible for these fields;

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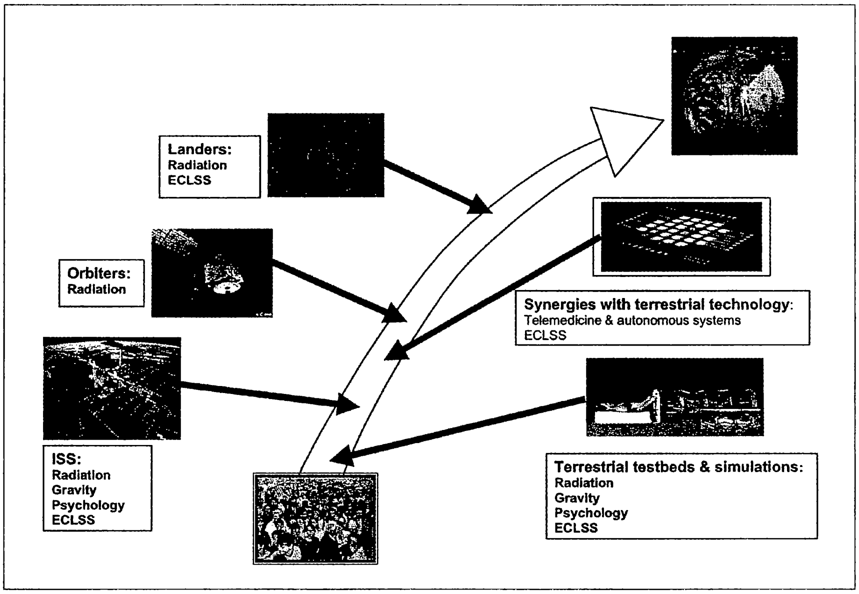

Figure 7.1: Roadmap recommended to ESA for a future European strategy for human exploratory missions to sustain human health, well-being and efficiency.

- analyses of existing databases for integrated performance modelling environments and risk assessments.

Hence, a roadmap for human-related aspects within a future European strategy towards long-term interplanetary missions, either to a lunar base or to Mars, should be based on:

- utilisation of forthcoming space missions and
- utilisation of terrestrial testbeds and simulation facilities (Figure 7.1).

For each element, the most demanding tasks, as identified in Chapters 4 to 6, are highlighted and approaches to accomplishing these tasks are proposed.

7.1.2 ISS, a milestone in life sciences and life support technology for human exploratory missions

The ISS is the ideal testbed for studying the effects of cosmic radiation on human health, as well as long-term human adaptation to microgravity and hypogravity, provided suitable on board facilities are available. As a confined environment in space, the ISS is also a suitable platform for developing and testing advanced life support systems. The unique opportunities provided by the ISS are also underlined by the recommendation of the ESSC-ESF, to include the ISS in the catalogue of "European Large Facilities". In human-health related issues, future research and development requirements may be grouped into three categories: (i) research required for risk assessment, (ii) surveillance and monitoring of the human responses, and (iii) development of countermeasures to minimise health detriments from the space flight environment. Figures 7.2 and 7.3 summarise the suggested research and development activities on the ISS, for radiation health and protection purposes and for human health issues with emphasis on protection against microgravity and low gravity effects. They need to be part of a long-term research programme that assures a systematic investigation of the different

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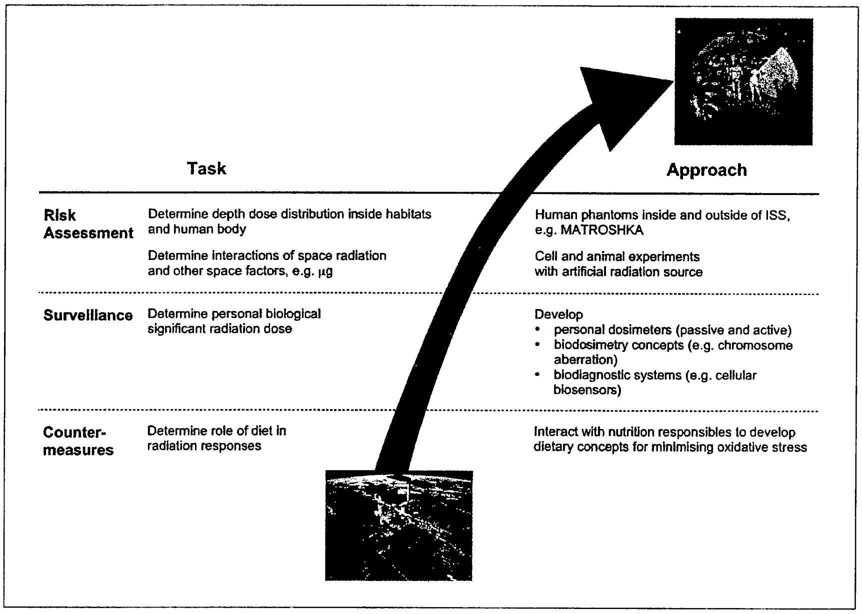

Figure 7.2: Research and development activities on the ISS for space radiation health and protection purposes within a European roadmap for human exploratory missions.

environmental and organisational variables most critical for Moon and Mars missions.

In radiation health issues, the main task is seen as the development of a new, and more appropriate, approach towards integrated risk management, which requires a redefinition of the criteria presently used for the ISS. It should include the repercussions on the overall mission success probability of radiation protection measures, such as shielding design or mission planning. 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 a purpose. Measurement campaigns on the ISS form an excellent tool for experimental validation of radiation environment models, of transport code algorithms and reaction cross sections. Several items which are required as base information for this risk management can be acquired by experiments and measurements on board the ISS (Figure 7.2).

In order to maintain crew health and operational efficiency during exploratory missions, a programme is recommended which includes research into:

- gravity-related health issues, such as on musculoskeletal disorders, neurosensory disorders, and orthostatic intolerance;
- general health issues, with emphasis on those phenomena which are considered to be specific to the mission scenarios studied, e.g. long-term stay in a closed environment, or which might be indirectly influenced by the spaceflight conditions, such as infectious diseases, neoplasm risk, endocrine, nutritional and metabolic disorders, general cardiovascular diseases, digestive disorders, and injuries;

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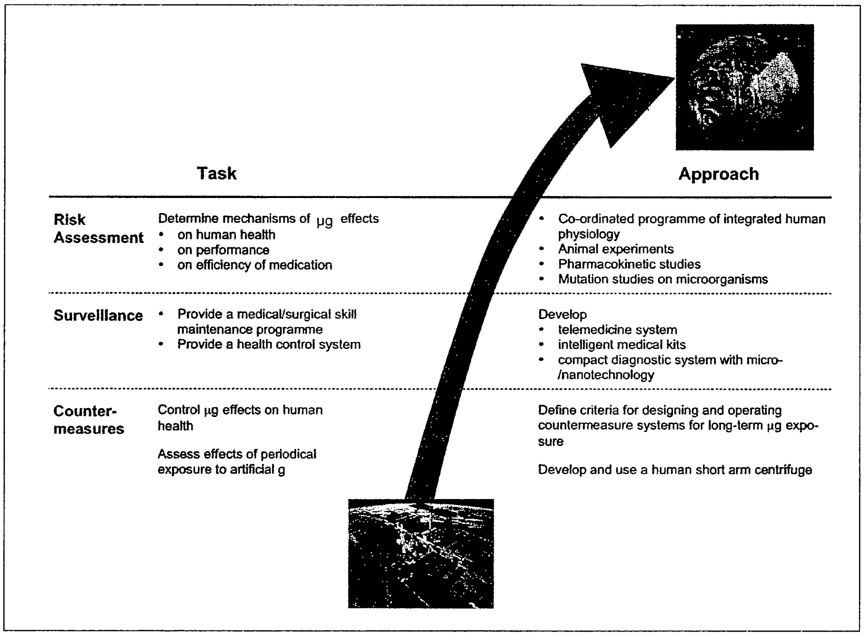

Figure 7.3: Research and development activities on the ISS for human health issues, with emphasis on protection from microgravity and hypogravity effects within a European roadmap for human exploratory missions.

- development of appropriate countermeasures in view of long-term exploratory missions.

Whereas some of this research can already be performed using short-duration space missions, e.g., taxi or Shuttle flights to the ISS, satellites, or terrestrial simulation facilities, the largest and most important part of these studies requires long-term exposure to the spaceflight environment as provided by the ISS (Figure 7.3) or comparable simulated conditions. These measures also have the potential to enrich various fields in clinical practice and health prevention on Earth.

It is important to note that, in particular, research and countermeasure-development related to individual adaptation to long-term confinement and isolation, interpersonal issues, and specific aspects of crew composition (e.g. mixed-gender or mixed-culture crews), which presupposes a sufficiently large number of subjects to allow for statistical analyses with sufficient significance, needs to be part of a long-term research programme. For psychological studies of the most critical variables for Moon and Mars missions (e.g. level of confinement, isolation, and crew autonomy, communication constraints), it is recommended to identify a common set of measures which are kept constant across studies and used for baseline assessments and later evaluation of crew behaviour and performance under different simulation/mission scenarios (Figure 7.4).

Current ECLSS functions/techniques are not yet sufficiently developed to meet the requirements of human exploratory missions. Investigations are required into advanced life support system technologies based on bioregenerative and supplementary physico-chemical technologies, and on natural resource utilisation, completed by extensive investigations into environmental monitoring issues. An

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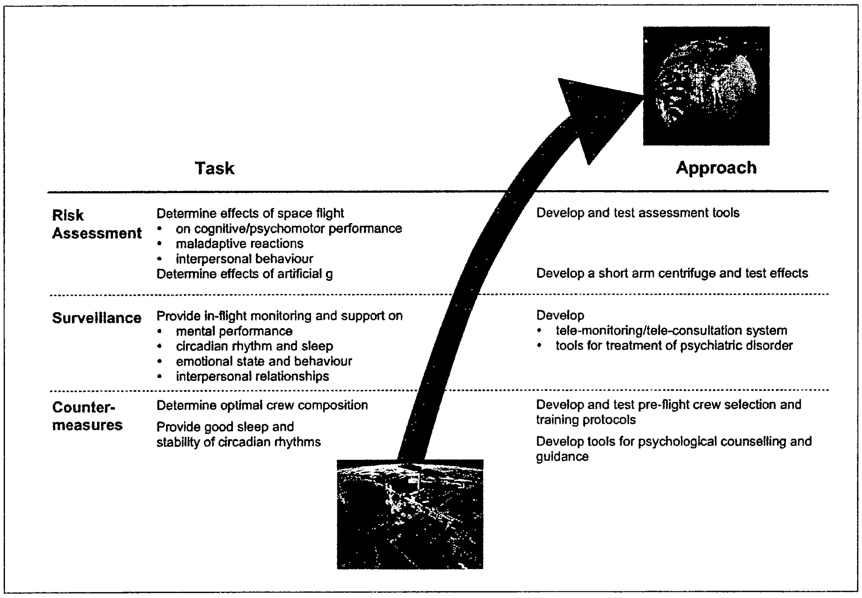

Figure 7.4: Research and development activities on the ISS in psychological issues within a European roadmap for human exploratory missions.

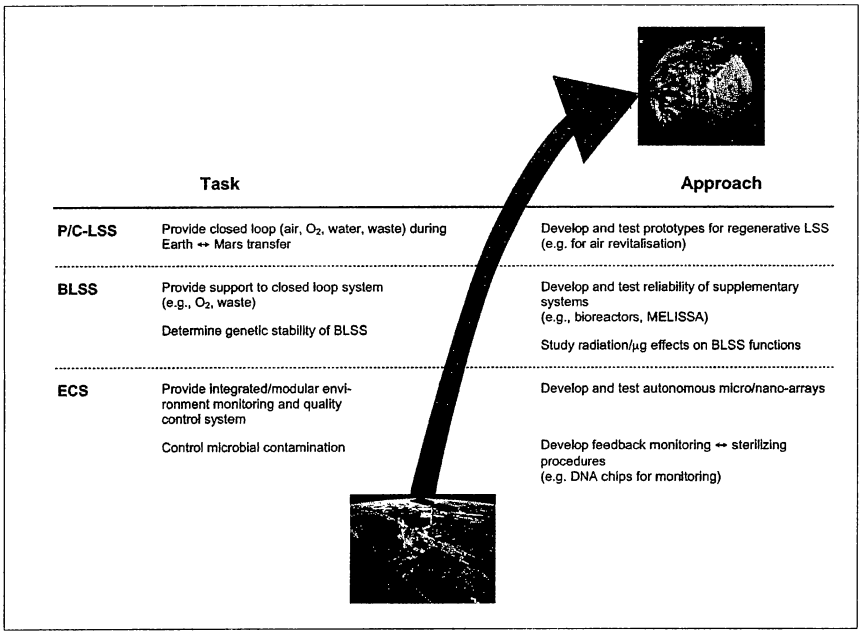

Figure 7.5: Research and development activities on the ISS for ECLSS development within a European roadmap for human exploratory missions.

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. Several technologies can already be tested and qualified on board the ISS (Figure 7.5).

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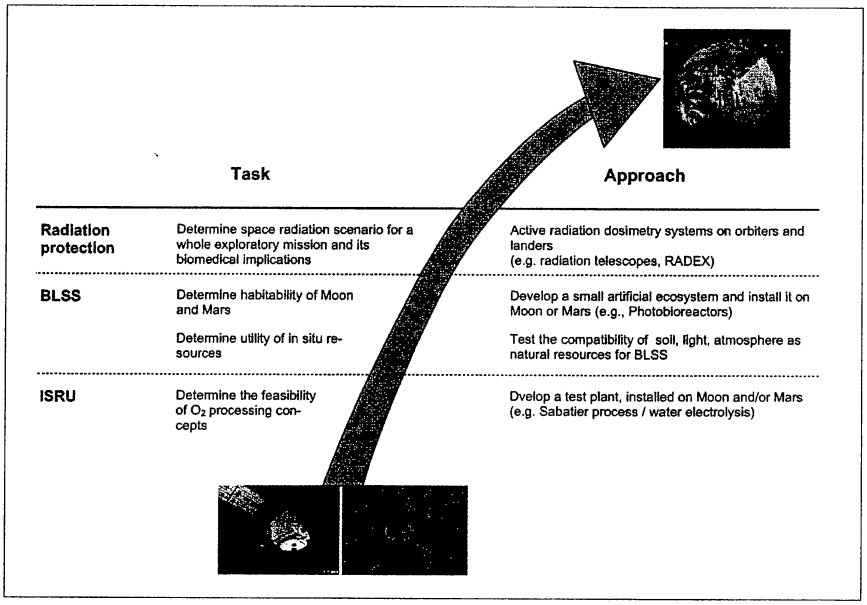

Figure 7.6: Research and development activities on robotic precursor missions within a European roadmap for human exploratory missions..

7.1.3 Precursor missions pave the way towards human exploratory missions

In order to improve and validate transport codes for prediction of solar particle and cosmic heavy ion radiation doses inside a given shielding distribution, at a given position in interplanetary space, at a given time within the solar cycle, robotic precursor missions are required to the Moon or to Mars (Figure 7.6). Robotic lander missions will provide data on the radiation climate on the surface and modes and efficiency of natural (e.g., regolith) and artificial (e.g., habitat) shielding. They are also valuable for pilot studies on BLSS and ISRU (Figure 7.6).

7.1.4 Terrestrial testbeds and simulation facilities

Whereas research onboard ISS is essential for all questions concerning the possible impact of microgravity, hypogravity, radiation, other space-specific factors – and potential interactions between them, other questions can be more appropriately addressed by ground-based studies in analogue environments and simulations (Figure 7.7).

7.1.5 Recommended European approach to developing future advanced life support systems

Planetary stations with a permanent crew and long-term interplanetary transfers (e.g., between Earth and Mars) are the main drivers for advanced life support systems developments:

- A lunar base is characterised by a small crew which will be replaced regularly. As a result, humans are expected to stay on the lunar surface for an unlimited period of time. The distance between the Moon and Earth is small enough to ensure regular logistical supply missions; if necessary, tools or equipment can even be supplied at short notice. Likewise, the emergency evacuation of the station crew and their transfer to the Earth could be arranged within a relatively short period of time.

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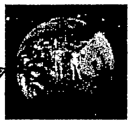

	Task	Approach
Radiation protection	Improve and validate transport codes Determine biological effects of single heavy ions Determine interaction of radiation with µg	Use heavy ion accelerators (e.g. GANIL, GSI) Use microbeams from heavy ion accelerators Use fast rotation clinostate at heavy ion accelerator
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 Determine human health and environmental monitoring and quality control	Install and test prototypes in habitable closed chambers Develop integrated/modular environment monitoring and quality control system by use of micro-/nanotechnology

1

Figure 7.7: Research and development activities using terrestrial testbeds and simulation facilities within a European roadmap for human exploratory missions.

- A human station on the surface of Mars will also accommodate a small crew for up to about 500 days. In contrast to a station on the Moon, the large distance between Mars and Earth does not allow a rapid evacuation of the station crew in case of emergency.

The ALS requirements (lifetime, reliability, robustness, maintainability etc.) for the two scenarios are therefore different. Common to both scenarios are:

- constant gravity, although lower than on Earth;
- no severe restrictions in space for habitat and supply facilities;
- natural resources available for utilisation (e.g., *in-situ* resource utilisation, propellant production, provision of materials for ECLSS/ALS),
- a practically unlimited amount of electrical energy.

In view of the experience Europe has already gained from previous space missions, it is recommended to focus on the following topics:

- *Interplanetary transfer missions:* Due to the limited space available onboard a transfer vehicle, most ALS functions will probably be provided by physico chemical technologies and bioregenerative techniques are anticipated to be of less importance for this type of mission. In this case, the main ALS requirements are low power and space consumption. This implies closure of the oxygen and water loop. Whereas techniques exist for closing the oxygen loop, new developments are required for closing the water loop, which could be of bioregenerative or physico-chemical nature. Although experience relevant to space is currently quite limited in Europe, water recycling methods for terrestrial applications are well developed. It is recommended to make this terrestrial knowledge available for space applications.

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- *Permanent lunar base*: If the base is located at the south pole (Scenario 1) with permanent (80-90%) sunlight, bioregenerative ALS activities will become increasingly important; however, ISRU techniques will probably play only a minor role for ALS purposes. The extraction of oxygen from the Moon regolith seems to be feasible, but the technical effort to do so is rather high. The potential use of ISRU technologies on the Moon becomes more likely and more feasible if the size of the crew becomes larger than foreseen in mission Scenario 1.

- *Long-term Mars station*: If humans stay for longer periods of time on the surface of Mars (Scenario 2), a complementary combination of physico chemical and bioregenerative ALS techniques is essential from the start. Bioregenerative techniques are suitable for supplementary food production, as well as for water and waste recycling processes. In addition, they support the air revitalisation function by photosynthesis (consuming an appropriate amount of gaseous carbon dioxide and producing oxygen). Since the habitats on Mars are expected to be quite spacious, sufficient room should be available for bioreactors, greenhouses and other bioregenerative and physico-chemical plants. These overall ALS techniques have to be complemented with techniques for natural resource utilisation and for propellant production.

All types of mission require a sensitive environmental monitoring system to indicate/identify/measure toxic substances or those that are considered to influence human physiological and physical behaviour.

So far, the maturity of European experience is quite different with regard to the different ECLSS and ALS developments:

- Existing physico-chemical techniques for air conditioning and revitalisation should be verified under microgravity conditions, preferably over a longer period of time as allowed by the ISS. If up-scaled accordingly, some of these techniques could be utilised in connection with ISRU technology. Techniques for environmental monitoring are available in Europe in space proven quality, but only for a handful of substances, in particular gaseous components such as humidity, carbon dioxide and oxygen. The number of measurable substances clearly has to be increased, as well as the measurement quality (accuracy, stability, repeatability etc.), and the handling of appropriate measurement equipment. Furthermore, the applicability of biosensors should be tested.

- Limited practical experience is available on bioregenerative ALS technologies for space applications. It is recommended to acquire a thorough knowledge and understanding on the impact of space conditions on the physiology (metabolism and genetics) and productivity of living organisms, and to develop BLSS technologies for culturing microorganisms and higher plants.

- Concerning natural resource utilisation, only theoretical knowledge is in general available in Europe, whereas concrete plans to conduct precursor missions to Mars with a downscaled ISRU/ISPP plant already exist in the USA. It is recommended to investigate whether available European ECLS technologies would be suitable for ISRU/ISPP purposes if adapted and up scaled accordingly.

In summary, it is recommended to perform an integrated generic evaluation/development of ALSS, combining bioregenerative and physico-chemical processes to achieve an optimal overall ALS/ISRU architecture, including appropriate environmental monitoring.

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7.2 Synergies with terrestrial industry and applications

The special needs connected with humans in space and the responsibility for their health, well-being and performance reliability, can, on the one hand be a driver of technological development and on the other may benefit from the rapid development of terrestrial technologies, especially in information technology, communication, biodiagnostics and biosensorics, and their miniaturisation. Figure 7.8 shows several examples of synergies with terrestrial applications, such as applications in health care, psychological issues and Advanced Life Support Technologies.

7.3 Conclusions and recommendations

From the critical assessment of the limiting factors for human health and performance and the definition of the life science and life support requirements it can be concluded that a human exploratory mission to the Moon or to Mars is feasible, in principle. However, substantial research and development is required in order to provide the basic information for appropriate integrated risk managements, including efficient countermeasures and tailored ALSS, as outlined in the Roadmap for a future European strategy in life sciences related issues for human exploratory missions.

Based on experience from previous studies on human missions in LEO – especially within the last two decades – and by use of terrestrial simulation facilities, the European scientific and technology community has gained substantial experience in assessing the risks for humans in this space

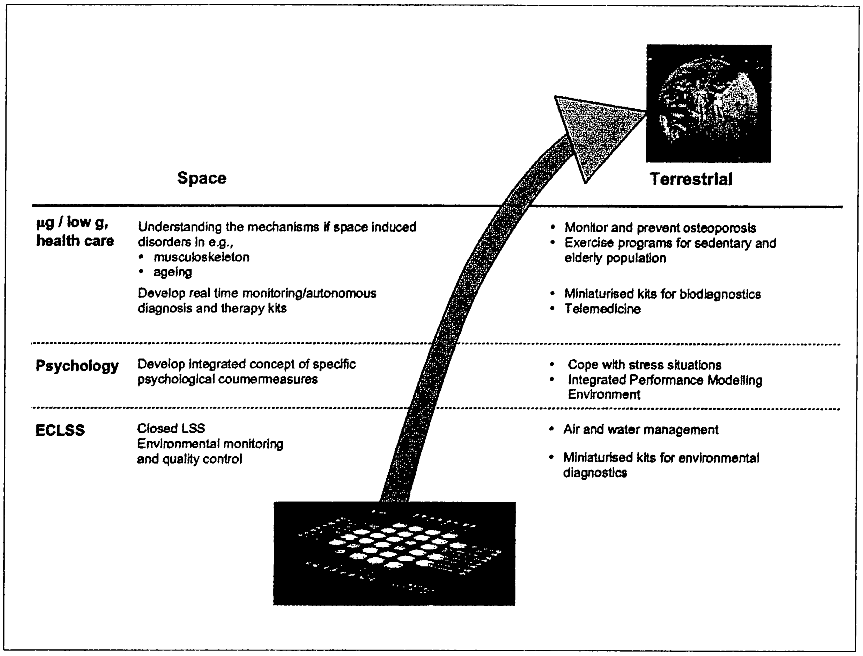

Figure 7.8: Synergies of space activities with terrestrial technologies and applications within a European roadmap for human exploratory missions.

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environment, especially in determining radiation hazards and the adaptation to microgravity, as well as in the development of 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 in the areas of radiation protection and human physiology, other partially new areas of research and technology enter the field, such as psychological issues, ALSS with bioregenerative life support systems, and autonomy in health and environmental control.

In order to be a effective partner in future 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 the Moon or Mars, and terrestrial testbeds and simulation facilities. Experience has shown that unusually challenging conditions as given by the human exploration programme, give extra impetus to 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.

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