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Technologies for Exploration

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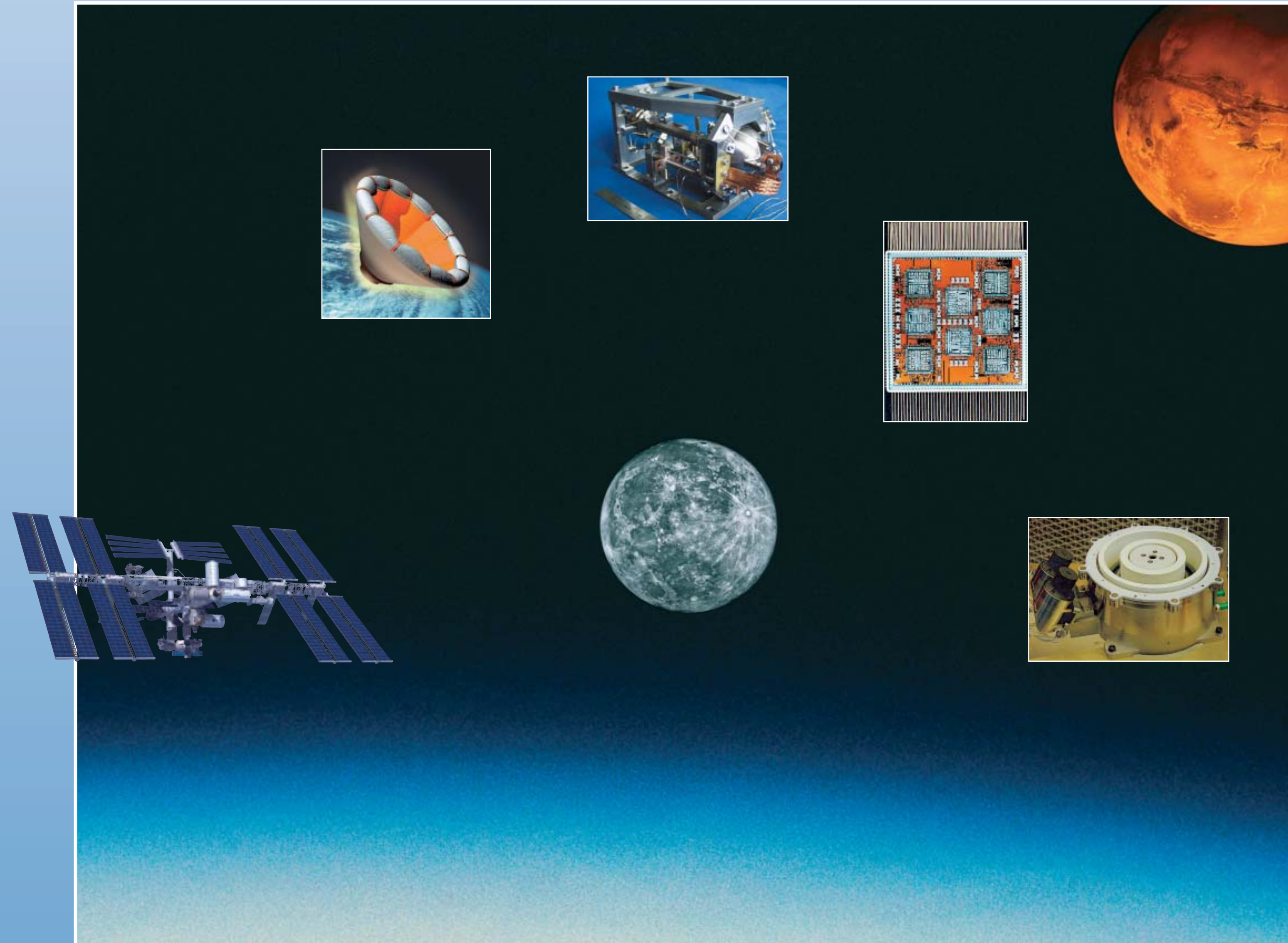

Aurora Programme Proposal: Annex D

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Technologies for Exploration

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Table 1. Exploration Milestones for the Definition of Technology Readiness Requirements.

2005-2010	*In situ* resource utilisation/life support (ground demonstration)
	Decision on development of alternative power sources
	Soft landing (Moon, Mars, asteroids)
	Interplanetary transfer stage
	In situ characterisation/resource utilisation test (Moon, Mars, asteroids)
	In situ exobiology (Mars)
	Communication network (Mars) / network of satellites
	Autonomous rendezvous & docking demonstration flight
2010-2020	Robotic precursor missions
	Sample return (Mars, asteroids)
	Knowledge base about humans 'living in space'
	Operational Moon mission (*In Situ* Resource Utilisation & life support)
	Man-rated soft-landing (Moon)
	Robotic planetary outpost / deep drilling
	Planetary 'Internet' capability (planetary relay satellites)
	In situ resources utilisation (Moon, Mars, asteroids)
	Closed-cycle life support
2020-2030	Infrastructure operational on martian surface
	Man-rated interplanetary transfer vehicles
	Man-rated soft-landing (Mars)
	Manned mission to Mars
	Human mobility on planetary surface

1 Introduction

This document provides an assessment of key technology areas for the Aurora Programme on Robotic and Human Exploration of the Solar System. Reference phases for exploration are defined within a preliminary scenario. This takes the status of discussion for the longer-term intentions in manned spaceflight into account and matches it with the known robotic exploration missions. This scenario is then overlaid with generic exploration missions, as suggested by the ESTEC workshop of April 2001 (see Section 2), in order to establish the timeframe for the required technology development.

Key technology areas are then defined and an assessment is made of the maturity of these key technologies with respect to the needs. The Technology Dossiers in the annexes provide a first definition of the corresponding technology development and cost plans.

A final overall funding profile is elaborated taking ESA internal (TRP, GSTP) and national activities into account as available. Only additional activities specific to exploration are listed. The resulting funding profile must be considered indicative only, especially for the later years, because of the preliminary nature of the mission scenario and defined exploration milestones. For the 3-year preparatory phase of the Aurora Programme, however, choices will have to be made on the most urgent generic technology developments, so that the resulting funding requests are in line with the available funding.

2 Exploration Milestones

For the purpose of this document, a sequence of Exploration milestones was derived on the basis of two sources. Firstly, from recent publications and press statements it was concluded that an international manned mission to Mars might be launched in 2030. Secondly, during the *Workshop on Robotic and Human Exploration of the Solar System*, held at ESTEC on 3/4 April 2001, scientists recommended the following sequence for planetary exploration: orbiters, landers, *in situ* robotic exploration, sample return, robotic precursors to manned missions, and manned exploration. This led to the definition of the reference Exploration Milestones in Table 1.

3 Exploration Missions

The milestones defined above and exploration missions already decided or in an advanced stage of planning set the timeframe for new missions that might be chosen within the Aurora Programme. Table 2 (p.4) shows approved and planned missions, demonstrating the compatibility of the proposed programme with the existing activities.

Table 2. Solar System Exploration Missions.

Planned Missions (Launch dates)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mercury			▼ Messenger (US)					▼ Bepi Colombo						
Venus														
Moon	SMART-1▼	Lunar-A▼	▼ Selene-A		▼ Selene-B									
Mars		▼ Mars; Rovers (US)▼		Rec. Orbiter (US)▼	Orbiter / Netlanders (F	▼; ▼ Marconi (I); ▼ Mars Lander (US)				▼	MSR (US-F)			
Jupiter & Moons							▼	Europa Orbiter (US) (3y)		▼				
Asteroids / Comets	Muses C▼	▼ Rosetta	▼ Deep Impact								▽ Rosetta Landing			
Saturn & Moons			▽	Huygens Titan Descent						▼	Titan Explorer (4y)			▸
LEO (ISS)	▼ ISS OP		ATV ▼	▼ Columbus										

Exploration Missions	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
A. Study Phase & Techno				▼										▽
B. Project Phases (B/C/D)														
Orbiters		(Asteroids, NEO, Mars)		▼				▼			▼			
Mars Sample Return (MSR)						▼					▼			
Landers (In Situ + Drill)				▼		(Mars, Moon, Asteroids, NEO)			▼					▽
Robotic Expl. (In Situ+Drill.+Rov.)							▼					▼		▽
Robotic Precursor (Mob.+Drill.+SR)									▼					▼
Manned Precursor														▼
C. Generic Technologies														
Solar Power			▼			▼			▽					
Electric Propulsion			▼			▼			▽					
Aerocapture/Aerobraking				▼					▽					
Alternative Power Sources									▼					▽
Power transmission						▼								
D. Orbiters														
Guidance & Navigation				▼	▼				▽					
Telecom				▼										▽
E. Landers														
Precision landing				▼					▼					
Drills				▼					▼					
F. Robotic Exploration														
Rovers							▼		▼					▽
ISRU 1				▼										
G. Robotics Precursor														
Descent / Ascent Propulsion				▼					▼					▽
ISRU 2									▼					
H. Human Exploration														
Life support						▼								▽
Man rated transport							▼							▽
Man rated Descent / Ascent									▼					▽
Habitability											▼			▽
Psycho / Physiology									▼					▽
ISRU				▼					▼					▽
Radiation and o-g comp.												▼		▽

4 Technology Development and Associated Cost

Once the mission phases are defined in the programme above, technology development schedules can be tied to it by requiring that a technology for a given mission must have reached a sufficient level of readiness at the start of the mission's Phase-B activities.

The elaboration of technology development compatible with the exploration programme defined above has also allowed identification of those technology areas for which work should be conducted immediately. The final selection of these areas and their proposed initial funding needs to take the following further criteria into account:

— The available funding through ESA's Technology Research Programme (TRP), General Support Technology Programme (GSTP) and the General Studies Programme (GSP). For 2001 and 2002, significant funding has already been allocated or is foreseen in areas of direct interest to exploration. Particularly relevant from this point of view are the ongoing technology development activities of the Agency's Scientific Programmes, most notably for BepiColombo. Overall, these activities will allow a smooth start in several areas of the Aurora Programme compatible with the limited funding available. For future years, continuation of these activities will be one the tasks of the Aurora Programme.

— The ongoing and planned activities of the national programmes. These aspects are dealt with in the Annexes to the best of the Agency's knowledge and will need to be revisited in the near future in close cooperation with the representatives of the national agencies.

— The generic nature of the technology and its applicability for a range of exploration missions, in line with the preparatory nature of the first 3 years of activities.

The definitions and considerations outlined above lead to the funding requirements listed in Table 3 (p.6). The overall level of resources quoted in the table is generally consistent with the goals of the Aurora Programme. Depending on the final mission selection in some areas, however, significantly higher funding would be needed for optimum utilisation and a consistent, well-structured enhancement of Europe's existing industrial capabilities. In other areas, it is expected that national programmes could provide a significant contribution. The proposed funding therefore has to be considered as indicative, with some elements still open for different contributions. In particular, for the years 2005/2006 it should be noted that significant hardware development is expected to take place and any change in priorities may have a significant impact.

During the preparatory period of the programme, the proposed investments will have to be scrutinised while taking into account the available funding

Table 3. Exploration Initiative: Preliminary Cost Plan (in € million).

Activity	*2002*	*2003*	*2004*	*2005*	*2006*
Control and Data Systems	0.5	1.2	2.3	3.8	5.0
Micro Avionics	0.2	0.9	2.2	3.0	3.2
Data Processing and Communications	0.4	1.5	1.9	3.0	3.8
Entry, Descent and Landing	0.9	2.0	2.9	3.5	3.7
Crew Aspects of Exploration	0.2	1.8	3.9	4.3	7.8
In Situ Resource Utilisation	0.2	0.7	1.3	2.6	2.6
Power	0.3	1.0	2.9	5.5	6.7
Propulsion	0.4	0.9	1.6	5.5	11.2
Robotics and Mechanisms	0.5	2.9	4.6	9.6	17.3
Structures, Materials and Thermal Control	0.9	2.3	3.2	5.5	5.5
TOTAL	4.5	15.2	26.8	46.3	66.8

and the European and national priorities. The prioritisation of the proposed development plan will have to take into account the potential cooperation with the international partners in the long term.

5 Conclusion

This document provides an assessment of key technology areas for the Aurora Programme on Robotic and Human Exploration of the Solar System. Key technology areas are then defined and an assessment is made of the maturity of these key technologies with respect to the needs. The technology dossiers in the Annexes provide a first definition of corresponding technology development and cost plans. These documents are intended as a reference for future work and will have to be further enhanced, taking into account in particular the ongoing industrial and scientific investigations, before converging on the definition of a European Framework for Exploration.

Annex 1

Automated Guidance, Navigation & Control and Mission Analysis

Annex 1 Contents

1 Automated Guidance, Navigation & Control

1.1 Introduction

Exploration missions, manned or unmanned, will be characterised by limited communication capabilities owing to long signal delay, limited bandwidth and intermittent opportunities. Automation of onboard processes is therefore required to achieve satisfactory response times and handling of anomalies.

Recent years have seen an exponential increase in the use of automation aboard space vehicles, caused by three driving factors: technology availability, the need to reduce operational cost, and the limitations in communications. The foundation for onboard automation lies in the control and data systems available onboard. Furthering this technology will therefore help to answer the increased demands of an exploration programme. These demands will initially come from the new capabilities required for unmanned vehicles. But as the mission value/cost increases, the requirement for higher success rate and the automated handling of contingencies will be demanded. When man is finally entering the loop, demonstrated flexible and failure-tolerant systems have to be available.

The technology studies in automated guidance & navigation control (GNC) performed in Europe over recent years are too numerous to list individually. There are many areas in which we have unique capabilities or specific strategic interests, but, focusing on the technologies specific to exploration, the following areas are of particular interest:

- automated rendezvous (system and sensor technologies), as being developed for ESA’s Automated Transfer Vehicle (ATV);
- launch vehicle trajectory guidance and control, in addition to the Ariane family of launchers;
- fault-tolerant onboard control and data handling. ESA’s Data Management System-Russia (DMS-R) has successfully provided the initial control for the International Space Station (ISS);
- man-machine interfaces, where European non-space industry has a lead;
- deep space GNC, surpassed only by the US by the number and success of deep space missions.

Automated rendezvous systems have undergone a long period of development in Europe, thanks to continuous support from ESA. The capabilities developed for ATV constitute the current end product. Beyond the overall automatic onboard system and its sensory elements of a short-range laser scanner (rendezvous sensor) and differential Global Positioning System (GPS) receivers for the medium range, the unique capabilities in terms of specific rendezvous analysis tools, simulators and dedicated test facilities (e.g. the European Proximity Operations Simulator) must be recognised. The development is therefore completed as far as the needs of manned low Earth Orbit (LEO) missions. But, if more distant missions are contemplated, the need for new developments becomes critical.

Launch vehicle trajectory guidance and control is sufficiently developed for expendable Earth-based launchers, and launcher-specific development programmes will likely support new developments. However, there are areas in which exploration introduces the necessity for specific capabilities. One large area related to reusability of launchers is reentry technology. There is a certain capability in this field available in Europe through such programmes as Hermes, the Atmospheric Reentry Demonstrator (ARD) and X-38, but nothing unique. Both Russia and the US have superior capabilities. It is therefore primarily the strategic importance of future reusable launchers that demands a drive for mastering this technology. Some developments are therefore expected to be supported by other programmes, but a strong effort will be necessary to address exploration-specific questions.

Fault-tolerant onboard control and data handling was developed for the ISS through the DMS-R project. This effort was based on early developments by ESA of a SPARC instruction set-based computer core (ERC-32). Development of cores has continued by adding digital signal processing capabilities based on ADS21020 and generic processor cores (Leon). At some point, the specific hardware needs of exploration missions will need to be addressed, but the current development in this field is so rapid that a specific effort for exploration is not yet warranted. The emphasis should rather be on the development of algorithms and architectures for later implementation in hardware.

Man-Machine Interfaces (MMIs) were initially intensively studied for applications in space through the Hermes/Columbus programmes. European industry in general has a world-class foundation in human-factor engineering and MMI. This effort should be continued in order to establish early on which role automation may play in assisting manned exploration, and what the performance requirements are for the automatic systems to be developed.

Deep space GNC is a collective term for the capability that provides the ground operational support during deep space missions, navigation for interplanetary manoeuvring, and systems and equipment for long missions in harsh environments.

In addition to these areas of traditional capabilities, Europe is in the process of acquiring significant capabilities for soft landing on other planets. Huygens is underway to Titan, Beagle2 is under development for Mars Express, and Roland is being developed for Rosetta. In addition, CNES continues the effort started at ESA for a MarsNet system of landers, potentially followed by participation to a sample-return system. Landing on a planet with an atmosphere is similar to Earth reentry during the initial phases of the entry and hypersonic flight, where deceleration, steering and other GNC aspects are governed by the aerodynamics. This area is therefore covered by the same reentry technology as identified above for launchers. Landing on a planet (or any target) without an atmosphere is very different, as retro-propulsive techniques must be used. There are similarities only in the very final stages of approach and touchdown.

When identifying areas to be covered by the initial 3-year development period identified in this volumes introduction, we must answer the question: ‘Why now, and not in 5 years?’ Many technology areas are in such rapid development (e.g. computers) that anything new developed now will likely be outdated in the 15 years leading up to a manned mission. It is therefore recognised that up-front developments must focus on those technologies with long lead times and those necessary for precursor missions.

The experience gained from developing ATV’s automated rendezvous is used for identifying the long-lead items. Most of the ATV problems were caused by the interaction between the development of the system concept (strategy, trajectory, etc.) and the new equipment. Initially a system study was performed during which equipment specifications were derived. A trade-off of equipment technologies initially selected the most promising for further development, but sometimes during the process a switch to other technologies was necessary, the system model had to be refined, and a new set of equipment specifications had to be derived. The development cycle had to be iterated before a workable baseline could be endorsed for final development for ATV. This interaction of system concepts and required specific equipment development is being recognised for the required entry and landing technology areas.

Precursor missions, likely to be automated unmanned vehicles for sample return, site survey, site preparation and technology tests, often place more stringent requirements on autonomy and miniaturisation. Notably, early exploration missions may be highly similar to today’s science missions, but as the demands on the system rise the invested capital and complexity will increase. These will demand increases in system robustness and survivability – difficult criteria to meet for the long-duration interplanetary missions. Specific studies to address these problems will therefore be needed.

From the discussion above, four control and data system technology areas have been identified that must be covered specifically by an exploration programme:

— Automated Rendezvous
— Entry Trajectory, Guidance and Control
— Landing Guidance, Navigation & Control

1.2 Automated Rendezvous

Rendezvous technology brings two free-flying space vehicles into contact, but excludes technologies related to contact dynamics, such as capture, docking and berthing. An exploration programme needs rendezvous technologies, both for the precursor missions (e.g. sample return) and all of the manned missions. Originally conceived as a method of reducing the mass of each launch by dividing complex systems into modules, current manned efforts cannot be envisaged without capabilities for crew rescue and logistics resupply.

There is a distinction between the needs of unmanned precursor missions, which are required to be fully automated, and manned missions, in which a crew can perform the rendezvous manually, maintain a supervisory role, or relinquish all control to an automated system. For unmanned systems, mass and other system resources are typically at a premium in order to reduce overall mission cost, while for manned systems reliability and robustness are the focus.

1.2.1 Justification

While technologies for manned LEO missions are mature, the specifics of unmanned scenarios and missions beyond Earth orbit must be addressed. Notably, if the target changes from a circular to an elliptical LEO, or to an orbit about a different body (Moon, Mars) or to deep space (e.g. L2), the dynamics change to such a degree that the overall strategy must be modified. For this reason, the rendezvous needs of exploration missions need specific attention, beyond what is covered in other programmes. Rendezvous for unmanned missions, such as a sample return mission, require improvements in sensor miniaturisation and performance. Similarly, manned missions to other locations need a replacement for the long- and medium-term navigation capability that is provided in LEO by GPS. Also, automated rendezvous systems for LEO applications are not fully autonomous. Monitoring and supervisory control by ground operators increase approach safety and mission success probability. In all rendezvous operations beyond Earth orbit, supervisory control is limited or impossible. For such applications, the onboard system has to be more autonomous, in particular concerning failure isolation/identification and mission recovery (re-planning) after interruption from a contingency. Previous developments have shown that these issues need to be addressed at an early stage in order to reach an iterative convergence between the system concept and the equipment capabilities.

ATV's automated rendezvous system is the most advanced in the world. Though the US has long experiences going back to the early 1960s, all US systems to date have involved man-in-the-loop for controlling the final approach. Development of an automated system was begun, but not completed. Russia has the longest and deepest experience in automated rendezvous and docking. System design and technology in use now for the ISS is based on 25-30 year-old technology. The Kurs radar-based system is a fully autonomous system for LEO applications. It is typically used on the unmanned Progress logistics vehicles for resupplying the ISS. Kurs is very large and heavy by today's standards, and cannot be considered for these reasons for applications beyond LEO.

Japan's recent ETS-7 mission demonstrated elements of automatic rendezvous. Though this was an engineering test, it is expected that development will be continued with the envisaged HII Transfer Vehicle (HTV) for resupplying the ISS. Its development hinges, however, on the successful completion of the H2A launch vehicle.

We can therefore justify the extension of Europe's lead in automated rendezvous by expanding the range of applications through the proposed exploration programme. The foundation of tools and test facilities are already uniquely available in Europe.

The end goal should be to develop a system applicable to both unmanned sample return from another planet (Moon, Mars and Mercury) and any of the conceived manned exploration missions. 'Develop' in the sense of this initial 5-year period should be understood as:

- pre-development of the elements needed for the manned systems to the level where a harmonised system concept and associated equipment are available;
- for unmanned missions to reach a maturity level where demonstration and early preparation missions can be performed.

1.2.2 Background

Development of a rendezvous capability in Europe began in the early 1980s as an enabling technology programme, and continued for Hermes and Columbus. The 3-year Rendezvous and Docking Pre-Development Program (RVD-PDP) laid the foundation in terms of simulation and analysis tools (ROSS) for the onboard GNC system, as well as equipment pre-development (rendezvous sensors, docking mechanism). The next step was the ATV Rendezvous Pre-development (ARP), consisting of the development and verification of a realtime onboard system, medium- and short-range sensors of flight quality, and flight demonstration of the sensor elements. First launch of the ATV project is expected in 2004.

European companies have therefore already built a significant expertise in this field. The following table summarises the capabilities of the most important players:

Astrium, Bremen, D	System and mission analysis. Control system design (Columbus, RVD-PDP, ARP)
Astrium, Toulouse, F	System and mission analysis, camera-type rendezvous sensor. Control system design (Hermes, RVD-PDP, ARP, ATV)
EADS Launch Vehicles, Les Mureaux, F	System and mission analysis Control system design (Hermes, ATV)
GMV, Madrid, S	System analysis
Saab, Gothenburg, S	Camera-type rendezvous sensor (not continued
Jena Optronic, Jena, D	Laser scanning rendezvous sensor

1.2.3 Planning

Further development of autonomous rendezvous has to build upon the current significant capability. Extensions must initially be sought through systems studies on the target orbits, longevity, robustness and mass optimisation. Specific hardware development will then be needed for relative navigation. This serves a dual purpose: specific developments for unmanned precursor missions, as well as a pre-development and demonstration effort for subsequent evolution to robust highly reliable manned systems. This way, the specific flight demonstration needs are kept to a minimum.

The first 2 years should lay the foundation through system studies and simulation tools. The next 2 years concentrate on developing hardware for the unmanned mission, along with developing higher fidelity simulators and the initial studies of manned missions. In the final year, the focus shifts to flight demonstration of the techniques for unmanned missions, while the development of manned systems are ramped up. Hardware development is, at this stage, funded only to the level necessary for supporting the demonstration missions. The development of man-related systems will have to continue significantly in the next 5-year cycle, but it can then be based on the findings of this first period.

On the above basis, the following define an initial set of studies, from which an expenditure profile for the overall effort was derived (Table A1.1):

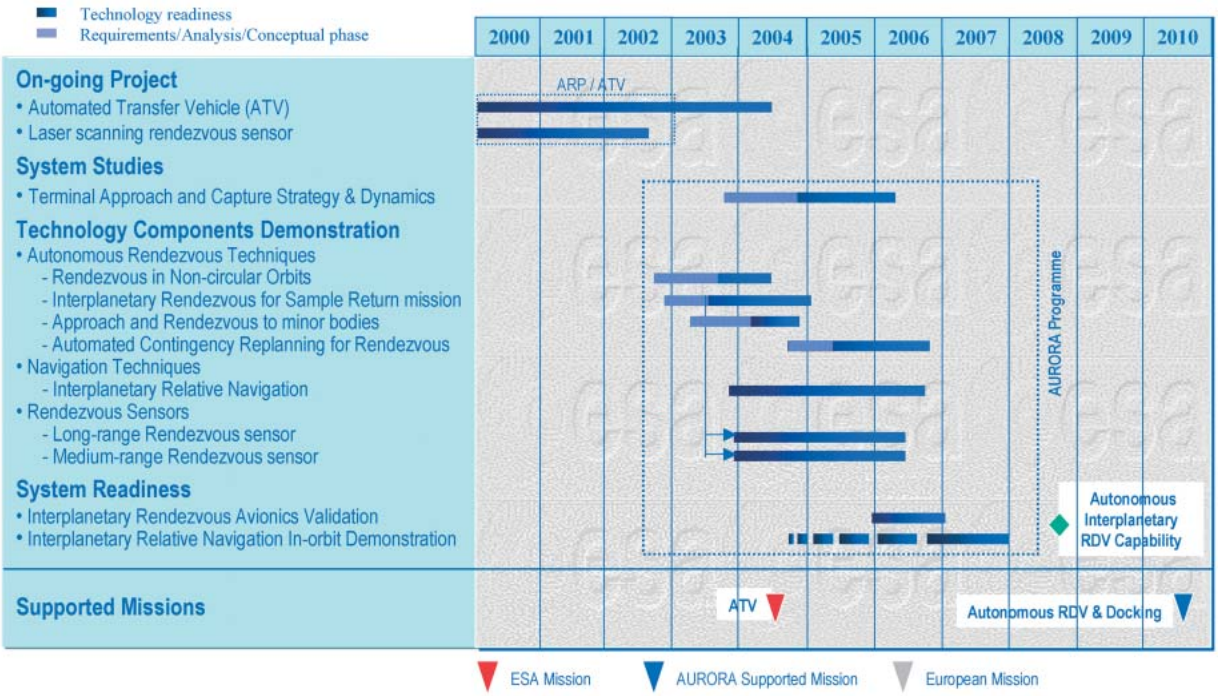
— Rendezvous in Non-Circular Orbits,
— Relative Navigation for Autonomous Rendezvous beyond Earth Orbit,
— Long-Range Rendezvous Sensor for Interplanetary Applications,
— Medium-Range Rendezvous Sensor,
— Interplanetary Relative Navigation Flight Demonstration,
— Automated Contingency Replanning for Rendezvous,
— In-Orbit Rendezvous for Sample Return,
— Approach to and Rendezvous with Minor Bodies,
— Terminal Approach and Capture Strategy and Dynamics.

1.3 Entry Guidance, Navigation and Control

Entry technologies, as identified here, are to a large degree common between Earth return (reentry) and the entry and landing on a planet. The only planet with a significant atmosphere of relevance for an initial exploration programme is Mars, as neither Venus or the outer planets can support the presence of humans. The atmospheric pressure on Mars is lower than on Earth, but the weaker gravitational field means that the pressure lapse rate is lower, so the martian atmosphere extends further from the surface. Technologies such as aerobreaking, aerocapture, entry deceleration and various atmospheric flight techniques are applicable to both Earth and Mars with many commonalities.

The effort identified here concentrates on the GNC aspects of atmospheric entry and hypersonic flight. Low-speed flight aspects are covered in Section 1.4, while non-GNC aspects such as aerodynamic shape, thermal control and hot structures must be covered by other elements of the exploration effort. Within GNC, guidance encompasses trajectory optimisation

Table A1.1: Preliminary Planning for Automated Rendezvous.



techniques to meet system and mission design constraints, as well as path replanning in the hypersonic phase for retargeting. Navigation is a unique problem because of the highly accurate surface relative information needed, and the problem of sensing in the high-speed regime when the vehicle in shrouded in a plasma flow. Aerodynamic data acquisition may be considered as part of the navigation problem. Various aerodynamic means must be considered to control the vehicle attitude and trajectory in a mass-efficient manner. In the latter case, the actuators are not considered as part of the control problem (and so not covered here), but should rather be identified and studied in the context of general hot mechanisms.

1.3.1 Justification

Whatever manned exploration mission is contemplated, the crew needs to return to Earth. Entry technologies are therefore applicable to any potential exploration mission. Moreover, if Mars is the target, more specific technology requirements have to be addressed. Additionally, related needs will likely arise for aerocapture and aerobreaking in order to reduce overall mission cost. For unmanned precursors, Europe's current capability is sufficient for ballistic flight systems. However, if more accurate targeting is required, such as several vehicles landing close to each other for a sample return mission, a new hypersonic steering capability must be developed. *Developments in this field are required if Europe is to have the capability of* in situ *investigation of specific locations.*

That European capability is not unique. Both Russia and the US have gained long experience from their more than 40 years of competition. Apollo, the Space Shuttle and Buran all offer steering capabilities better than is available in Europe. Japan has been active to a lesser extent, through its HOPE mini-shuttle development efforts. The justification for Europe's participation is therefore not to be found in a superior capability, but in the strategic importance of the field. If we embark upon an exploration programme, there will likely be room for several players, as demonstrated by the Crew Return Vehicle cooperation between NASA and ESA. The area is large enough to encompass several players, and the study and use of multiple techniques.

Entry technologies will likely be studied in the context of launchers (reusability) and manned flight to LEO. For exploration missions, the focus is likely to be on capsule shapes entering at relatively high speed. Additionally, the Mars environment demands specific attention for both unmanned or manned missions.

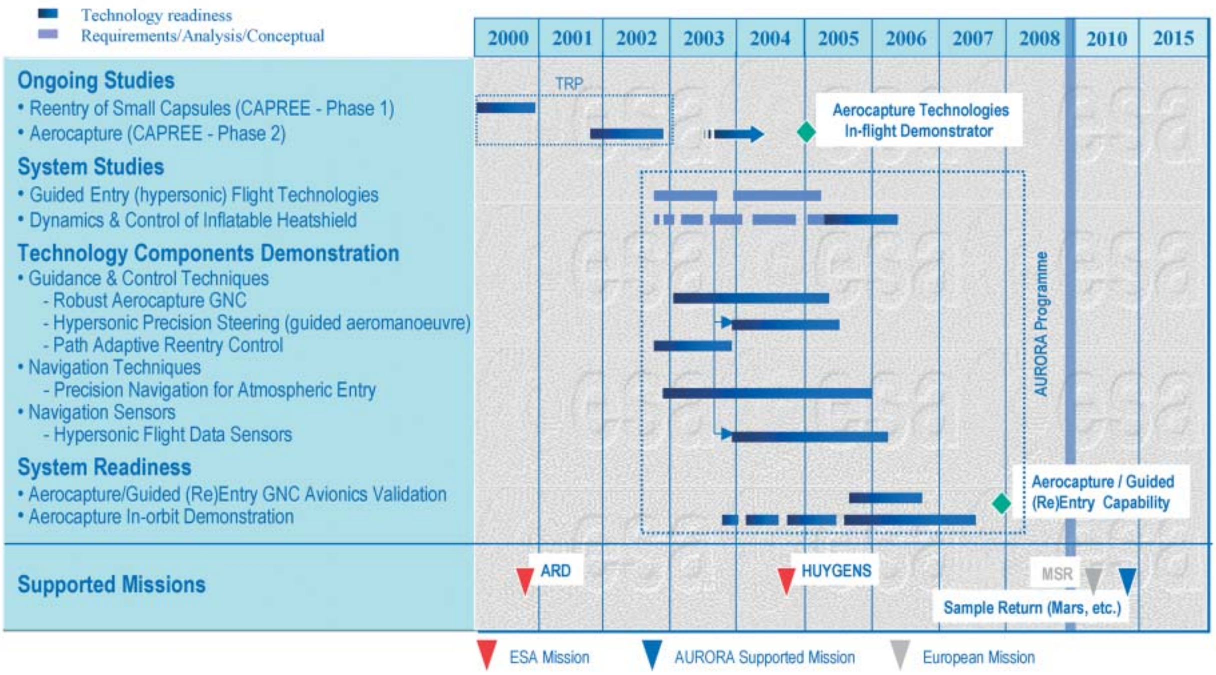
The goal of the proposed effort for the initial 5-year period should be seen as the successful development and demonstration of a steerable (re)entry capability. In its simplest form, this may encompass further development of the asymmetric capsule shapes being currently studied, but it may be extended to include winged and/or flexible vehicles such as required for a reusable launcher. Demonstration of the developed technology is seen as a key issue.

1.3.2 Background

European preeminence in launch vehicle development is exemplified by Ariane and studies such as FESTIP (Future European Space Tranportation Investigation Programme) and FLTP (Future Launchers Technologies Programme), which included reuseable vehicles. Europe's innovations in launcher trajectory guidance and control are less well-known. The ALTOS tool provides a unique flexible and powerful package for handling all kind of launcher trajectory optimisation problems, ranging from air-breathing multistage rockets, to various reentry stages. New optimised guidance systems have been developed for the Ariane family, and other techniques have been studied for entry flight of Hermes and Saenger. Control of such vehicles is often difficult because of the dynamics and interactions between trajectory, attitude, environment, system design constraints and vehicle flexibility. Though other countries may have superior flight experience, specific technical solutions studied in Europe may offer the potential for superior systems.

ARD is the only demonstration mission in which Europe has flight experience of active control during (re)entry. Current efforts include the steerable mini-capsule studied within the CAPREE project, set to develop unique guidance and navigation capabilities, and ESA's involvement in X-38. CAPREE is a TRP technology effort, while X-38 is a large flight demonstration effort in collaboration with NASA that includes ESA participate in GNC issues. As for planetary applications of entry technology, Europe's efforts so

Table A1.2: Preliminary Planning for Entry GNC.



far are limited to ballistic flights (Huyens, Beagle2), with little or no active GNC issues.

1.3.3 Planning

Initial efforts must focus on a down-selection of the areas to be covered. This will likely happen in coordination with other development efforts. Once a few key areas for the exploration effort have been determined, a pre-development effort similar to that for rendezvous will have to be initiated. An initial guess at these key areas has been made, and is presented below in the form of individual studies. Again, it serves the sole purpose of identifying an envelope for the overall effort. These areas include the steering capability to target a specific site (focusing on asymmetric capsule shapes), a specific navigation system in the case of a planetary mission, and air data sensors.

— Hypersonic Precision Steering for Planetary Entry of Capsules
— Path Adaptive Reentry Control of Design-Limited Vehicles
— Aerocapture Guidance and Control
— Atmospheric Flight Control for Planetary Missions
— Entry and Hypersonic Flight Technologies
— Reentry Flight Demonstration
— Hypersonic Flight Data Sensors
— Dynamics and Control of Inflatable Heatshield
— Navigation for Atmospheric Entry

Starting from the initial down-selection in the first year, the second year concentrates on the development of simulation and analysis tools to consoli-

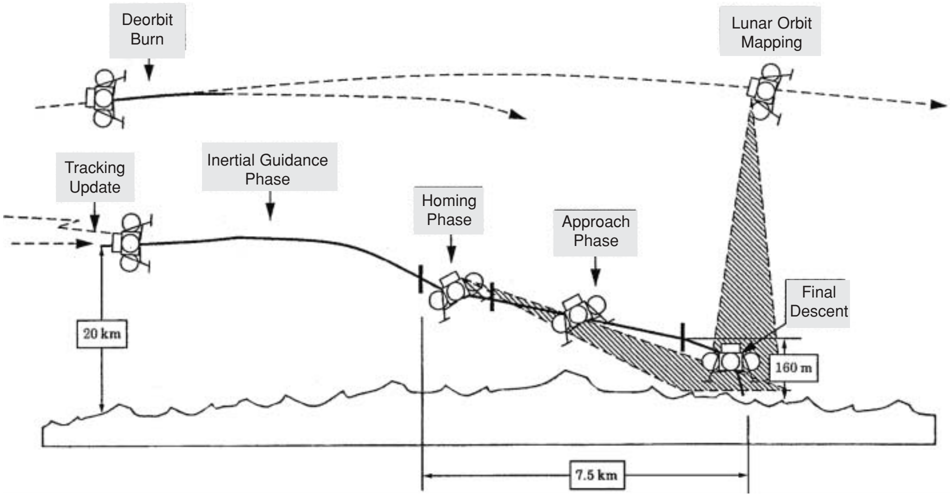


Fig. A1.1: Landing GNC requirements for a lunar mission.

date requirements on equipment and systems. The second and third years see the major developments in preparation for a demonstration flight encompassing as many as possible of the developed technologies. It is expected that, on the basis of the findings from this pre-development effort, a choice can be made in 2005 of the potential European contributions in this field to an exploration mission. Once this is done, the further development required in the second 5-year cycle is relatively limited. It is, however, mandatory to do this development up front, in order to make the appropriate decisions in 2005. See Table A1.2.

1.4 Landing Guidance, Navigation & Control

Landing here applies to large and small bodies, with or without an atmosphere, including the Moon, Mars, asteroids and even Earth in the case of a returning crew or sample (Fig. A1.1). For bodies with a significant atmosphere, landing is differentiated from the entry problem by addressing only the final low-speed approach and landing phases, in which aerodynamic forces play a lesser role. Retro-propulsive techniques are demanded in the absence of an atmosphere, but are equally well applicable to landing in an atmosphere. With an atmosphere, additional techniques such as parachutes, parafoil or rotary wings may be contemplated. A fixed-wing solution is less suitable because of the need for a prepared 'runway'.

1.4.1 Justification

Although a reference mission has not been defined for the exploration programme, it is assumed that mastering landing technologies will be required. Hard or semi-hard (e.g. airbag) landings are options for early automated missions. As the complexity and value of the landed vehicle increases, however, soft controlled landings with a high success rate and/or an ability to handle anomalies will be demanded. The estimated 20% mission loss rate during landing has to be significantly improved.

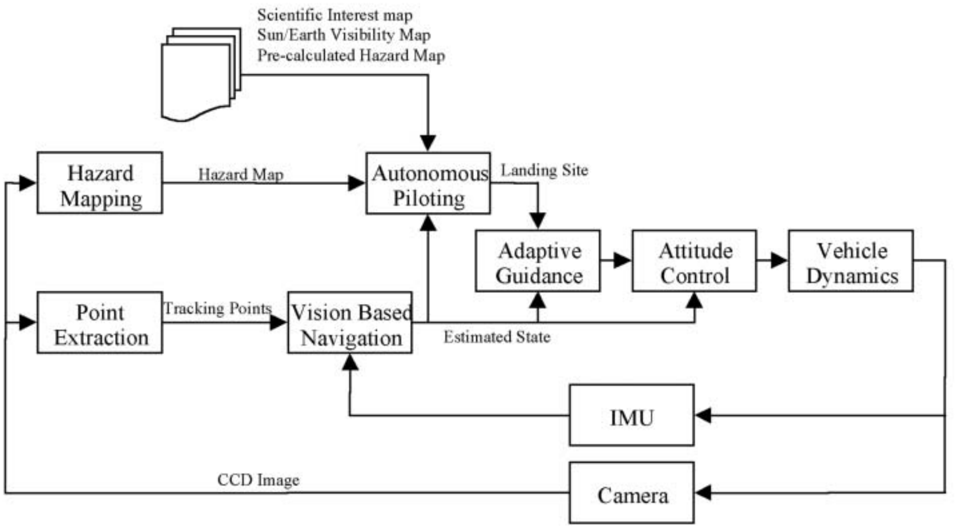


Fig. A1.2: Camera-based landing system.

Only Russia and the US have performed successful planetary landings. Only NASA remains active in the field, with a large array of developments in support of the planned Mars missions. In some cases, however, the heritage from previous projects appears to slow the level of innovation. An example of this is the repeated use of the heavy radar-based approach sensor developed 30 years ago for Viking, as opposed to newer camera (Fig. A1.2) or laser-based techniques studied in Europe and Japan. Japan does have a significant development effort in support of missions such as Muses-C and Selene, although a lack of coordination between NASDA and ISAS is slowing development. Europe, with its developments in support of Rosetta, Mars Express and BepiColombo, is well positioned to take the lead in this field.

The end goal of the development effort proposed should be perceived as mastering the technologies required to deliver a high value cargo safely to the surface of another planet. This will allow to consolidate Europe's position as an au-par partner to US in this field, and a leader vis-à-vis the rest of the world. Only in this way can Europe maintain an autonomous capability to deliver and perform experiments on the surface of another planet. Alternatively, the system may be offered as a contribution to a joint mission, as it may be seen as a reasonably isolated system.

1.4.2 Background

Studies on planetary landing were initiated in Europe with the preparation activities for the Rosetta mission proposal. The *Comet Approach and Landing System* study focused on a radar-based automated descent system requiring limited onboard computational resources but with a significant mass impact. A different approach was taken in a follow-up series of studies focusing on vision-based systems (COPNAV, HRPBT). From the initial

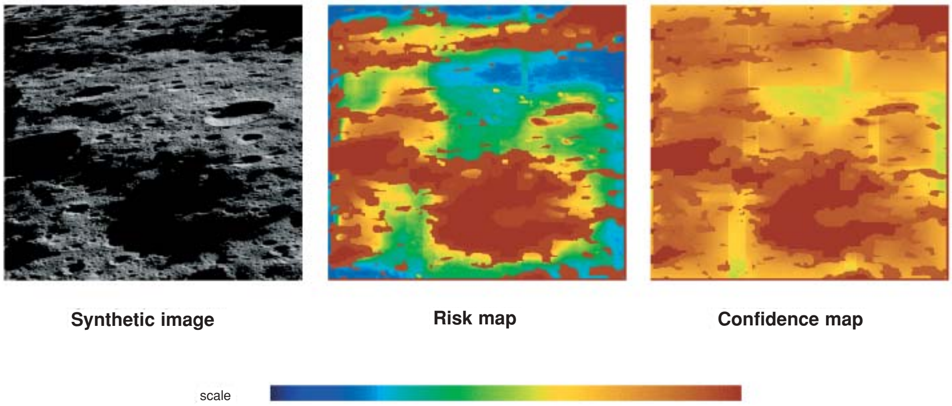


Fig. A1.3: The feasibility of automated selection of a landing site has been demonstrated.

development intending to land the complete Rosetta vehicle on a comet, the mission being implemented has a separate orbiter relying on a combination of optical and NASA Deep Space Network (DSN)-based navigation for comet approach, and a lander (Roland) without any onboard navigation or control system. The use of a ballistic uncontrolled trajectory down to the surface is possible in this case only because of the target's low gravitational field.

While Rosetta relies mostly on optical means to navigate down to the surface, Huygens will use measurements of deceleration to trigger the sequence of events for descent to the surface of Titan. An onboard range-sensing radar will provide more detailed surface-relative altitude measurements during the final phases. While Huygens was not primarily designed to survive the landing and perform surface science, the capabilities developed for the descent system is an important technological achievement.

In the mid-1990's, a specific interest in lunar missions was identified. This led initially to a number of internal ESTEC studies on various lunar lander concepts (LEDA, ELSPEX and EuroMoon). In parallel, industrial studies (LLS, IVN and VBNL) supported the development of landing technologies and identified the areas that needed emphasis. In particular, the contract on Integrated Vision and Navigation for Planetary Exploration (IVN) was instrumental in establishing the feasibility of a number of potential landing technologies. Advanced hazard-mapping techniques were integrated with online agents acting as a pilot in order to select the most suitable landing site in real time (Fig. A1.3). A vision-based navigation system provided ground-relative tracking to ensure a soft landing. Although the achievements were impressive, only the feasibility was demonstrated and significant development is still necessary.

Though little came out of the studies in terms of missions, concepts were proved and capabilities developed that formed a significant input to the current efforts for defining the BepiColombo Mercury Surface Element. It is within this project that these technologies are being furthered today.

Beagle2 forms a development branch much on its own, separate from the ESA efforts, largely because of the funding scheme. Through recent changes in the project set-up, this effort is becoming more coordinated with the others.

The following is a summary of landing technology development efforts so far in Europe:

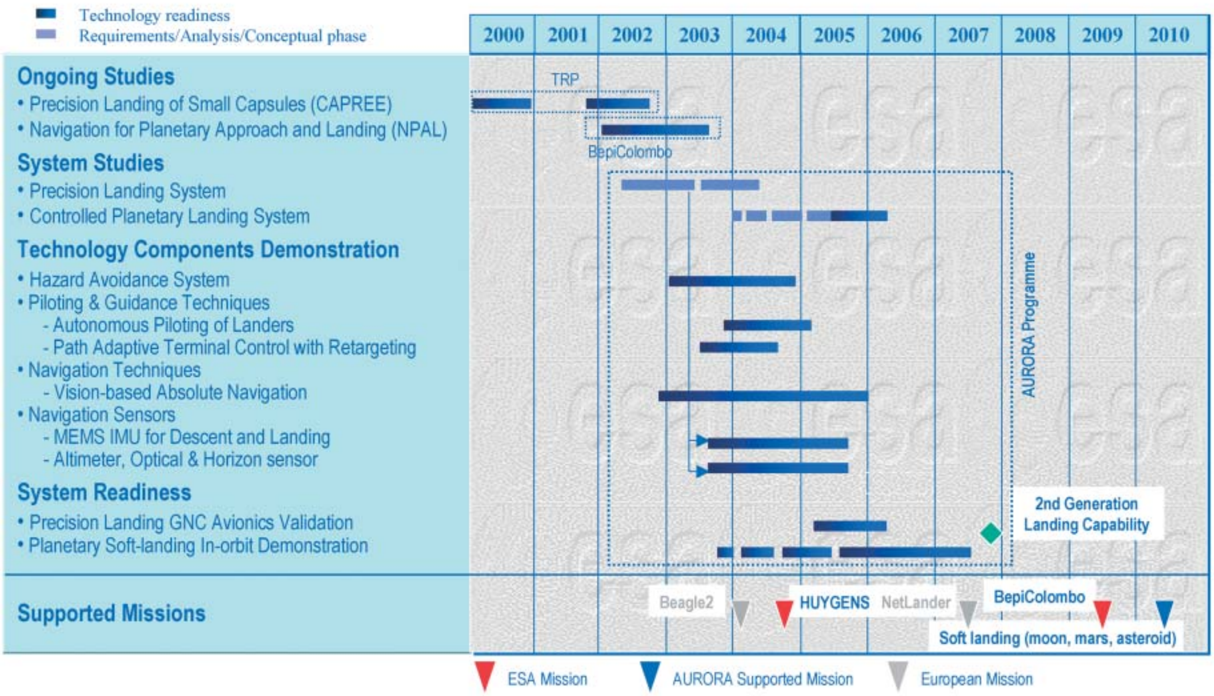
Comet Approach and Landing System (CALS) 1988-90	Officine Galileo	I
	Selenia Spazio	I
	FIAR	I
	NFT	N
	AME Space	N
	CNR-IAS	I
	U. of Roma	I
Lunar Landing System Study (LLS)	Matra Marconi Space	F
	GMV	S
Integrated Vision and Navigation for Planetary Exploration (IVN)	Aerospatiale	F
	Fokker	NL
	INRIA	F
	DIST	I
	JoR	A
High Resolution Planetary Body 3D Model of Terrain (HRPBT) 1990-95	JoR	A
Vision Based Navigation for Moon Landing (VBNL)	JoR	A
Huygens Landing System Development		
Huygens Descent Radar	Ylinen	FIN
Beagle2 Landing System Development		
Roland Landing System Development (COPNAV)		

Lander technologies are to a large part specific to planetary missions. There are, however, cases in which relevant technology has a broader range of applications. One such is the development of a smart camera system for lander navigation through interest-point tracking, currently being considered under ESA's space science core technology programme. This camera and its related components have potential applications on Earth observation and manned spaceflight missions, as well as specific terrestrial industrial processes.

1.4.3 Planning

The capability currently available or under development in Europe focuses primarily on the delivery of relatively small hard-landing packages. Once more valuable payload is involved, methods of trajectory control (throttle-able engine), hazard avoidance, abort scenarios and improved navigation methods must be developed. As identified in Section 2 for rendezvous and docking, this will require an iterative development of strategies, systems and associated equipment. The following is therefore a preliminary list of

Table A1.3: Preliminary Planning for Landing GNC.



conceivable studies necessary in order to reach the desired level of maturity:

— Hazard-Avoidance for Automated Landing of High-Value Cargo
— Autonomous Piloting of Landers
— Path Adaptive Terminal Control with Retargeting
— Precision Landing System Study
— Navigation for Return to Base Missions
— Micro ElectroMechanical System (MEMS) Inertial Measurement Units for Descent and Landing
— Vehicle Touchdown Control
— Vision-Based Absolute Navigation above Planetary Terrain
— Abort Strategies for High-Value Cargo
— Controlled Planetary Landing System Study
— Planetary Landing Demonstration Flight (Selene type)

The development process suggested in this funding profile corresponds to an initial system and technology concept study phase along with the early development of the analysis tools (1.5 years). Following is a period of system and equipment pre-development, in order to consolidate the expected performances. The next step is a demonstration effort through flight tests of specific key areas. This demonstration effort is expected to bridge over into the next 5-year period. It is also expected that mission-specific developments will have to follow in the next 5-year cycle, but the pre-developments proposed here should significantly ameliorate the involved risk. See Table A1.3.

Table A1.4: GNC Preliminary Funding Profile (in € million).

Activity	*2002*	*2003*	*2004*	*2005*	*2006*
Automated rendezvous	0.1	0.2	0.3	0.6	1.5
Entry trajectory, guidance and control	0.2	0.5	1.0	1.6	1.5
Landing guidance, navigation & control	0.2	0.5	1.0	1.6	2.0

1.5 Conclusion

Three areas for technology development in support of Solar System exploration have been identified. The overall suggested funding profile for the five initial years is given in Table A1.4 on a 2001 price basis.

In addition to the coverage of the above-defined technology areas, it is strongly recommended to embark on a precursor mission for the development, testing and demonstration of a soft-landing capability. Such a mission should test as many soft-landing technologies as possible: autonomy, hazard avoidance, propulsion, piloting, range and rate sensors, operational procedures, design principles and tools, touchdown systems, control during ground contact, energy absorption systems etc. Many of these technologies cannot be tested to a satisfactory level on Earth. The Moon forms a natural nearby target to perform such tests at a reasonable cost. If no specific payload requirements are imposed, it is believed that such a test vehicle can be developed for less than €50 million once the needed technologies are individually funded. Launch should be targeted for about 2006. An alternative would be to participate in the Japanese Selene missions, but the readiness in NASDA for cooperation is perceived as low at this stage.

In addition to the above-defined Automated GNC activities, a specific propulsion need has been identified. To perform a precision landing on a planetary surface, some method of throttling the applied thrust is necessary in order to compensate for downrange dispersions. None of our currently planned landing missions has such a trajectory-correction capability. In the internal studies performed, the problem was circumvented by the use of multiple thrusters operated in an off-modulated manner. This is possible only for relatively small landers (as in the above proposed demonstrator mission) using small thrusters. A throttleable thruster is therefore needed, whose overall thrust level depends on the mass of the payload to be delivered. Which propulsion technology is used (storable or cryogenic) is immaterial, as long as a minimum throttle ratio of ±20% is guaranteed.

2 Mission Analysis

2.1 Introduction

Missions in the Solar System are challenging in terms of their high orbital energy requirement. A traditional way of gaining energy during the mission,

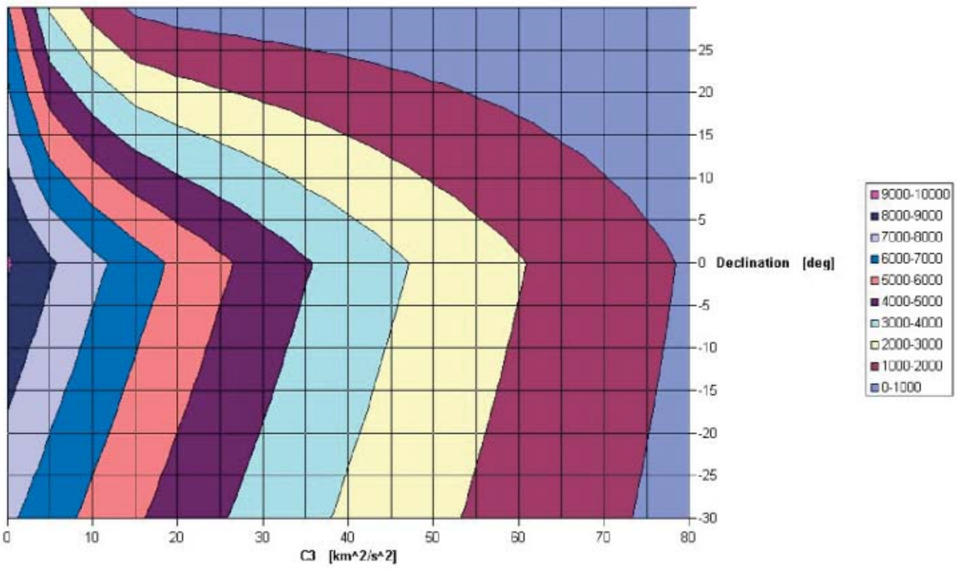


Fig. A1.4: Ariane-5 ECB estimated mass performance in terms of C3 (square of escape velocity) and declination of the asymptote.

thereby reducing the launch energy requirement, is to include gravity-assist manoeuvres with planets during transfer. This is a popular procedure, applied successfully during many interplanetary missions. However, ways of finding the most efficient sequence of gravity-assists are still not trivial, particularly if impulsive or low-thrust mid-course manoeuvres are included.

Gravity-assist manoeuvres are not the only way of borrowing orbital energy from the massive bodies of the Solar System. A more subtle method is to make use of the Weak Stability Boundary (WSB) properties in the vicinity of the Lagrange points of a Sun-planet or planet-moon system. WSB trajectories allow a reduction of planetary escape or arrival energy. It is proposed here to further investigate the benefit of such procedures.

Finally, defining optimum trajectories for reaching a given target in the Solar System does not guarantee that such trajectories can actually be flown. The navigation along the trajectories needs to be assessed in order to verify that the gravity-assist manoeuvres can be performed and that the final target can be reached with the desired precision. This is particularly crucial with exotic trajectories including WSB, low-thrust arcs and aerobraking during gravity-assist.

2.1 Specific Programme Proposals

2.2.1 Interplanetary Transfer Optimisation

2.2.1.1 Background and Justification

To find an optimum trajectory from Earth to a planet or a specific orbit in the Solar System is not trivial. An optimum trajectory means that the initial Earth escape velocity (launch energy) is within reach of cost-effective launchers and the sum of the mid-course and final manoeuvres does not excessively penalise the spacecraft's propellant budget. Such optimum trajectories usually involve intermediate planetary Gravity Assist Manoeuvres (GAMs). They provide velocity increments during transfer at almost no cost, but finding their proper sequence is still an art rather than a science. Once an adequate GAM sequence is found, there are procedures available for optimising the trajectory to any desired accuracy. The main problem is to find a suitable initial sequence.

2.2.1.2 Planning

Defining a suitable sequence of GAMs for a given mission requires solving a global optimisation problem. Algorithms expected to handle the problem with good chance of success include Genetic Algorithms. These have been applied successfully in the search for WSB trajectories and they may be a good candidate for finding suitable GAM sequences. An initial effort in this direction is therefore desirable.

Once a suitable GAM sequence is found with the help of Genetic Algorithms, it is expected that the same method may be used to refine the trajectory by replacing the procedure's rough analytical approximation (linked conics) by more refined models (patched conics or matched asymptotic expansions). This should be done in a second phase.

These methods are to be applied to the simple case of GAMs separated by coast arcs and also to cases when mid-course manoeuvres, impulsive or low-thrust are included. In a final refinement of these methods, powered swing-bys (impulsive, low-thrust or aerobraking) should also be included.

In all of the cases to be considered, the optimisation has to include the launcher's performance in the escape orbit, allowing the selection of a suitable launcher for the mission (Fig. A1.4 shows the estimated Ariane-5 ECB performance for escape missions).

2.2.2 WSB Planetary Arrival Trajectories

2.2.2.1 Background and Justification

For the case of a transfer from Earth to the Moon, WSB trajectories have offered significant saving in lunar capture DV. The use of Sun-Earth WSB trajectories allows a reduction in the energy of the arrival trajectory at the Moon, and the subsequent use of the Earth-Moon WSB allows capture into a lunar orbit at no cost (Fig. A1.5). For an Earth to Mars transfer of the Mars Express type, a Sun-Earth WSB trajectory combined with lunar swingbys have also shown a reduction in escape velocity requirements. These encouraging results suggest that WSB trajectories should be used for reducing velocity requirements for capture into a planetary orbit.

For the case of a mission to a planetary moon, WSB trajectories could be used twice:

— first, the Sun-planet WSB would reduce the ΔV for insertion into an orbit around the planet,

— then, the planet-moon WSB would allow easy capture into an orbit around the moon.

These two WSB manoeuvres could be combined with moon swingbys.

2.2.2.2 Planning

The benefit of using WSB trajectories for reducing capture ΔV for insertion into an orbit around a planet is to be assessed by analysing practical cases:

— arrival at a terrestrial planet (typically Mercury),
— arrival at a giant planet (typically Jupiter).

For the Jupiter arrival, combination with swingbys around the moons should be investigated. Then, the case of a moon as a target body should be investigated, where the planet-moon WSB is used, possibly combined with swingbys with other moons.

Finally, a low-thrust mission to Jupiter using solar electric propulsion should be analysed. Although solar power is not efficient for outer Solar System missions, it is still the only alternative for Europe to cover the energy need of a Jupiter mission. As very large solar arrays are needed for covering the energy requirements on orbit around Jupiter, it is natural to use these solar arrays as a source of propulsion power during the cruise phase. In this case, a problem is encountered at Jupiter arrival, where a large velocity impulse is needed for capture, involving chemical propulsion and constraining the solar arrays to be retracted (a risky operation). However, if WSB techniques allow the arrival ΔV to be small enough to be performed with a low-thrust engine, then the entire mission can be accomplished at low thrust, without any need for chemical propulsion. This would make the mission extremely efficient. The feasibility of such a mission should be analysed.

2.2.3 Advanced Interplanetary Trajectory Navigation

2.2.3.1 Background and Justification

Classical navigation for interplanetary missions involving long coast arcs, impulsive mid-course manoeuvres and planetary gravity-assist manoeuvres is well mastered by ESA, as demonstrated by Giotto. However, modern techniques for travelling in the Solar System make use of exotic techniques such as:

— solar electric propulsion resulting in long low-thrust arcs,
— planetary gravity-assist manoeuvres involving powered swingbys (impulsive or low-thrust) and aerobraking,
— WSB trajectories.

They all pose new challenges in navigation methods and need to be investigated.

2.2.3.2 Planning

Navigation including low-thrust manoeuvres combined with planetary gravity-assist is to be investigated first. It is urgently required not only for

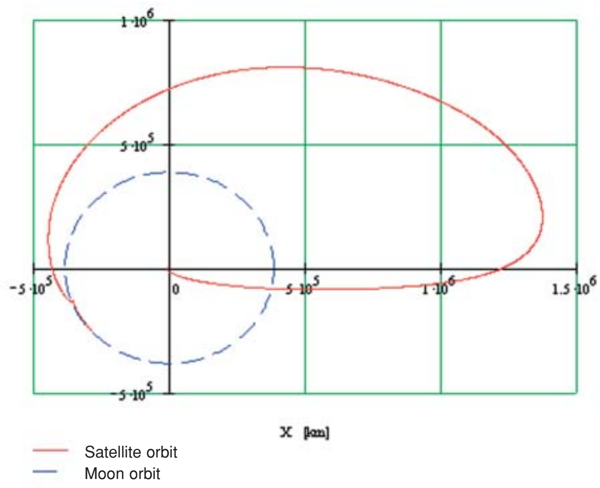


Fig. A1.5: WSB trajectory from Earth to Moon.

the Aurora Programme but also for some ESA-approved missions such as SMART-1 and BepiColombo.

In a second phase, particular attention should be given to the inclusion of manoeuvres during gravity-assist (powered swingbys), which can be of three types:
— impulsive (chemical propulsion) during swingby,
— low-thrust (electric propulsion) before, during and after swingby,
— aerobraking during swingby for planets with an atmosphere.

The investigation should first concentrate on the feasibility of performing such a manoeuvre successfully. In other words, can navigation be precise enough to create a swingby having the desired effect on the orbital parameters?

Finally, navigation along WSB trajectories proposed for capture into an orbit around a planet or a natural satellite Should be investigated. For each class of trajectories, ground-based and autonomous navigation should be considered.

2.3 Conclusion

Three areas of improvement in support of mission analysis for Solar System exploration mission have been identified:

— optimisation of interplanetary transfer trajectories, including gravity-assist manoeuvres (unpowered, powered or with aerobraking) and low-thrust arcs,
— the use of WSB trajectories for planetary capture,
— advanced interplanetary trajectory navigation.

These topics can be covered by performing corresponding studies with a total funding of the order of €0.4 million.

Annex 2

Micro-Avionics

Annex 2 Contents

1 Introduction

1.1 Background

The term ‘avionics’ covers the hardware and software elements that, on an aircraft or spacecraft, provide the data acquisition and processing, the command distribution, transducers (sensors and actuators), onboard data communications and ‘flight segment’ of the space link (ground-space communications). This set of informatics/telematics equipment constitutes the brain and nervous system of the spacecraft and is critically important to the mission success.

The term ‘micro’ denotes the need for mass optimisation. The imperative is amplified by an order of magnitude if the mission includes a lander, and by a further order of magnitude if it includes sample return. It is expected that the miniaturisation will build upon the constant progress in micro-electronics. However, to be effective at system level, the miniaturisation has to be understood as a system-level optimisation process, which includes considerations proper to the internal architecture of the avionics system as well as its position in the overall spacecraft system.

1.2 System Issues

Decoupling of the functional/performance specifications from the implementation

On a standard spacecraft, the avionics implement the command and data management functions and the attitude and orbit control/guidance navigation control function. A key requirement for systems on deep-space probes, where each kilogram has to be justified, is to achieve a good decoupling of the avionics’ final implementation from the performance and functional specifications of the different subsystems to be supported, in particular the command and data management and the attitude/orbit and guidance/navigation control. The reason is that the design of the avionics should optimise the implementation based on objective criteria of mass, power, volume, reliability etc. while meeting the mission objectives and related constraints (operations, environment).

Global optimisation versus local optimisation

The avionics already constitute a ‘system’ connected to different elements of the spacecraft: other subsystems and payloads. The miniaturisation effort has to be consistent end to end. When looking to existing state of the art avionics systems, it is clear that a drastic miniaturisation of the central electronics alone will have little impact, from a system perspective, if it is not performed in a ‘system’ approach that includes the minimisation of harness and connectors by setting up smart sensors and interfaces and by using a sensor or field bus.

Impact on other subsystems: power/energy – thermal

The mass or volume gain at the avionics level has to be balanced in a system approach. If the mass reduction is not accompanied by a power reduction, the benefit at system level will be reduced by retaining large batteries and large solar panels (Rosetta). If miniaturisation is not accompanied by a power reduction, thermal dissipation problems will occur with solutions (active cooling, heat pipes) that may hamper the initial benefit. At mission level, the emphasis is often on energy minimisation rather than power minimisation, but the instantaneous peak power is of more concern for the power subsystem design. For example, a power peak cannot be avoided on a Mars Lander to power the transmitter during a communications window. For deep-space probes with long communications delays to Earth, it calls for some autonomous adaptability of the resources management system to the local conditions.

Environment
Another concern is the environment met by the spacecraft at other planets, especially if there are surface or subsurface operations:

Mercury : 180ºC (poles), 270ºC (equator)
Venus: 400ºC / 90 bar
Mars: daily temperature cycling from –120ºC to 40ºC (winter), –60ºC to 20ºC (summer) near the equator (worse near the poles)
Jupiter: each satellite has its own environment (e.g. Europa) but jovian vicinity and orbit is a demanding radiation-harsh environment (>300 Krads)

Technologies that are less sensitive to thermal and radiation effects are preferred in order to minimise the mass of thermal (heaters, coolers) and radiation (shielding) protection.

1.3 Logical Steps
Logical steps for the development are:

1. For the near- to medium-term, prepare the technology for efficiently supporting robotic (in a wide sense) exploration missions at horizon 2010, with the following constraints:

   Take into account the state of the art
   The development of future avionics systems must take into account the status of the overall informatics and telematics technology. Any basic research activity in a field like micro-electronics amd computer science requires a level of resources that cannot be afforded by a space agency alone. The avionics technology effort will build on the established state of the art (technology that has gone through the natural selection process in the industrial or commercial worlds) and focus on the delta work required to adapt a selected subset to space.

   Technology evolution and hardware
   Micro-electronics and computer systems are in constant evolution, whereas the space industry looks for stable products. This apparent dilemma has to be solved by taking into account that avionics is a generic technology with a high prospect for recurring use. Technology evolution should be a built-in characteristic of the micro-avionics toolbox to allow for

a high prospect of reusability and interoperability as key issues for cost-effectiveness. Solid technology development should aim at making validated products (toolbox) available to the exploratory missions, while technology evolution will be smoothly introduced into flight systems by upgrading the toolbox. For this purpose, the micro-avionics must rely as far as possible on well-established industrial standards for the onboard interconnections, covering all the design levels from on-chip to the platform. A side effect is that commercial-off-the-shelf (COTS) can be used, if allowed from an environmental view-point.

Technology evolution and onboard software
A large part of the knowhow of both the command and data management system (including the upper level of onboard autonomy) and the AOCS/GNC system will be built into the onboard software. To keep the benefit of reusing application software from mission to mission without losing the capability of technology evolution is a must for a long-term exploratory programme. It will then be important to decouple the application software from the underlying layer by providing a basic software layer that provides the applications with the services they expect to receive and which are system-dependent but to a large extent are technology-independent.

Technology and system
Many software issues that have arisen in many ESA projects under recent reviews are fundamentally system issues that come from the initial definition or capture of incomplete requirements. For the exploration programme, tools are required to support the unambiguous capture of the mission and system requirements to both hardware and software specifications, and to provide implementation that can be traced up to the final integration and test.

System on a chip
In micro-electronics, engineers started to design at transistor level, then at gate level, then at macrocell level (flip-flop, ..). Today, the quantum used by designers to make one chip are complete functions such as a microcontroller, a floating point unit or a packet telecommand decoder. It is generally known as a ‘system on a chip’. It is promising but offers new challenges: cost, testing, quality, embedded software and hardware/ software codesign.

Reconfigurable/evolvable hardware and system
A new possibility offered by technology evolution is the concept of evolvable hardware and systems. This emerging field is expected to have a major impact on deployable systems for space missions and applications that need to survive and perform at optimal functionality, possibly for long durations in unknown, harsh and/or changing environments. This includes missions to comets and planets with severe environmental conditions and long-duration autonomous observatory missions. It includes in particular bio-inspired computer architectures. However,

although the potential is high and many active research & development activities flourish in these domains, most of them have not reached the level of maturity required for introduction in space systems in the short- or medium-term. For this reason, and in relation with the Reference exploration phases and in preparation of the 2010 goals, the near/ medium-term focus, with emphasis on reconfigurable architectures, should be:

i. Very large-scale (reprogrammable) FPGA
The capacity of current very large-scale Field Programmable Gate Arrays (FPGAs) is about 10 million gates. Even if, as with many COTS products, their use in space creates concerns, they offer the capability of using the same hardware for totally different functions during different phases of the mission. A lander mission is a typical case.

The use in space of these devices should be considered either in a COTS-based design where fault-tolerance is provided by dedicated peripheral functions or by the FPGA manufacturing process itself (rad-tolerant programmable FPGA). A typical application is in small-lander avionics, where the functions to be supported before and during the landing are very different from those to be supported after.

ii. Ultra large-scale integrated circuit (ULSI, geometry < 0.18 μm)
Looking at the technology roadmap and the evolution of the on-chip density (millions to billions of gates and the possible resulting pin-count of 600-1000), the current design paradigm used in processor architecture will not be applicable in the future because of the exponential rise in the complexity of design validation and testing). The system-on-a-chip approach is a solution for the near-term by extensively reusing already-validated functional cores. However, in the longer term, this approach will not sufficiently exploit the full capability offered by ULSI technology. The challenge is use the full capability of ULSIs while keeping affordable design, validation and testing phases and providing extensive on-chip fault-tolerance. In computer science research & development, a large theoretical knowhow has been capitalised in multi-processing and massive parallelism (data-flow architectures, cellular automata), and that should be exploited to propose efficient architectures that are evolvable or reconfigurable by internal rerouting of the control and data flow, and are resilient to single and multiple radiation-induced events.

2. For the horizon 2015, the logic is the same. The avionics toolbox used for the first generation of explorer missions will be adapted to include advances in computer science, including artificial intelligence, micro-electronics and photonics.

3. For the longer term, we must prepare the technology for manned space missions on the assumption that:

- there will be still a need for the support of advanced highly integrated tools, including avionics systems,
- the avionics emphasis is on fault-tolerance with repair capability, while on automated missions it is on reliability.

It can be expected that techniques and technologies that are today in the basic research field, such as quantum computing and large-scale evolvable, self-repairing systems, will become available for operations in space.

2 Technology Item Descriptions

Avionics offer a very high prospect for recurring use. This prospect is even higher for a dedicated programme such as the proposed Exploration of the Solar System. It will then be important to emphasise the possible recurring items from other programmes as well to identify recurring elements internal to the programme.

2.1 Micro-electronics

A prerequisite for any lead role in Solar System exploration is the need for a European capability in micro-electronics.

Rad-tolerant bulk CMOS technology

There is only one company remaining today with a rad-hard capability – AMEL of the US. It is a general concern for European space industry and for projects like Galileosat that need to be independent of external suppliers. In order to alleviate the problem, the concept of 'radiation tolerance per design' is under investigation.

Silicon-on-Insulator Complementary Metal Oxide Semiconductor (SOI-CMOS)

SOI-CMOS is a key technology for a programme devoted to the Solar System exploration. Compared with bulk CMOS, SOI combines several characteristics required by exploration missions: very low power, extended temperature range (up to 300ºC) and radiation tolerance.

Highly dense interconnect packaging

Highly dense interconnect packaging can be used an alternative method of miniaturisation: MCM (multi-chip modules) or V-MCM (also called 3D stacking). These techniques are available to the avionics designer. While they add cost at the development level, they bring a significant mass/volume reduction to recurring elements (such as mass-memory modules) or provide mission-enabling technology, like 3D packaging for a planetary penetrator to resist deceleration up to 10 000 *g*.

2.2 Main Building Blocks

Microprocessors and onboard computers

These support the command and data management system, including the onboard autonomy at platform level, and the attitude/orbit and guidance/ navigation system. They constitute the 'brain' of the platform and at the highest criticality level. In most cases, the onboard computer must fail-op/fail-safe in cold redundancy. In critical mission phases such as orbit/trajectory insertion and rendezvous/docking, hot redundancy might be required. The design of the avionics for automated probes with a potentially long lifetime are mainly reliability-driven.

Telemetry formatting and telecommand decoding
As part of the command and data management system, this function interfaces the radio-frequency tracking, telemetry & command (RF TTC) system in conformity with the CCSDS space links standards. Receiving the commands from Earth and distributing high-level direct commands for reconfiguration, it is at the highest level of criticality aboard a spacecraft and it is generally in hot redundancy to allow ground control access to the spacecraft in any situation (link permitting).

Spacecraft controller function
Combining the Central Processing Unit (CPU) and the TTC system, plus some basic Input/Output, creates the spacecraft controller function. It is part of all the space segment and surface elements. Owing to this high prospect for recurring use, it is proposed as a 'system on a chip'. The definition of the spacecraft controller includes a module specification and a standard peripheral extension to expand the basic functionality of the spacecraft core to mission-tailored additional functions (e.g. mass memory, payload processor) at unit level.

Data storage: mass memory module and unit
Data storage is an important issue in planetary probes because of the problems of communicating with Earth. The manufacture of very high-density memory chips (SDRAM, Flash) is beyond the capacity of rad-hard foundries. Designing a mass memory then takes a typical COTS approach. Together with highly dense packaging techniques, like 3D packaging, it is expected that, for many explorer missions, the required mass memory will be of small volume and accommodated within the same unit as the spacecraft controller on its peripheral extension. A standard file system support will be defined, such as the application software requesting the mass storage services. It is independent of the technology used inside the memory itself.

Data storage is an important element of spacecraft autonomy. Beyond the requirement for storing telemetry acquired during the non-visibility periods with Earth, larger databases will be required as more sophisticated autonomous behaviour is gradually introduced. This part of the storage must be non-volatile so that the spacecraft can restart from a lost-in-space/zero-power situation after a major failure.

Onboard data communications – user interfaces
In past projects, the standardisation effort was essentially devoted to the interconnection of different units. The push towards miniaturisation now calls for standardisation at all levels of the design, from on-chip to platform,

including modules and intra-unit. The standards will be selected from industrial and international standards, in agreement with other space agencies to ensure interoperability and portability between equipment and scientific instruments. It should be derived from a commonly agreed list of services to be supplied by the avionics to the users (application level). A standard user interface (physical and logical) should be defined for the purpose of the European exploration programme. It would also allow a 'plug and play' interoperability and portability from mission to mission, while providing a technology independence versus the physical/transport layer used for onboard communications that may evolve with technology. It will be the role of the mid-layer hardware and software to accommodate this evolution transparently to the user.

Harness
Harness mass represents 7-8% of a typical spacecraft's dry mass, increasing to 10% for some Earth observation missions. Of this, half concerns the cables and connectors required by the data handling (data/signals). Of this budget, it appears that a very large part of the harness does not come from the main TM-TC databus but rather from all the small transducers (sensors like thermistors, commands and their status relays, etc.), since a spacecraft has generally of the order of 1000 connections of this type. It means that tens of kilograms of copper are not intensively used – and some never used because they are connected to cold-redundant parts. This is not acceptable for an advanced exploration programme, where every kilogram has to be justified to the taxpayers. Further analysis shows that this situation is the heritage of a technology and system approach that is 20 years old.

It is expected that the size of the harness will be significantly reduced by introducing smart sensors and their interfaces (sensor/field bus) and standard user interfaces. For example, local reconfiguration and power-switching commands would be routed via the data bus, avoiding the doubling of today's power-switching performed at the power distribution level by individual switching commands at equipment level. A second-order optimisation should be considered by introducing wireless onboard data communications. Beyond that, wireless communications provide flexibility for the designer.

Basic software
The basic software providing the standard services of the avionics should be implemented and delivered together with the hardware. It is considered as a 'reference implementation', provided as an open-source software to allow easy maintenance of the software during an extended life-time compatible with the Aurora Programme.

Application software: system engineering
Firstly, the effort should be devoted to identifying the recurrent part of the application software that can then be optimised (especially for supporting autonomous onboard operations). Secondly, the system engineering approach for generation of the application software should be a direct

derivation of a formal specification. To be effective, it should include the use of computer-aided engineering (CAE) tools to support the capture of the user requirements, including modelling and formal proof when possible.

3 Status

3.1 Micro-electronics

Rad-Tolerant CMOS

The only company in Europe with this capability is ATMEL Wireless and Microcontrollers (originally MHS/TEMIC, now owned by the US company ATMEL). Alternative options under study include a standard CMOS foundry using specific rad-hard libraries (rad-hard by design approach), where the radiation-tolerance is achieved on commercial fabrication lines with special designs and process enhancement. In the USA, Honewell, BAE Systems (ex-Lockeed-Martin), Sandia and UMC have rad-tolerant processes. In Japan, HIREC has the capability of producing space-qualified application-specific integrated circuits (ASICs) and components.

SOI-CMOS

Although Europe has active SOI-CMOS laboratories (B, CH, D, F), there is no commercial foundry or chip manufacturer using this technology, although Thomson was a pioneer in this field several years ago. LETI under a contract ffrom DGA (F) has demonstrated very interesting results in radiation-tolerance (total dose and SEU) using this technology coupled with specific cells libraries. SOITEC (F) is selling SOI wafers worldwide, particularly in the USA and Japan. Marin (CH) is manufacturing very low-power nanocontrollers using SOI. In the USA, there are several companies handling both commercial ground applications (IBM) and aerospace (Honeywell). The Jet Propulsion Laboratory (JPL) uses this technology in several of their research & development projects. Honeywell uses it for rad-hard and high-temperature products.

Packaging

Astrium (Vélizy, F) and Alcatel have capabilities for producing space-quality MCMs. The Small- & Medium-Enterprise 3DPlus (a Thomson spin-off) is successful in the space, military and commercial markets with their 3D stacking technology, at a lower cost than US competitors like Irvine. Most US aerospace companies have MCM capability, which is also extensively used in military systems.

3.2 Avionics Building Blocks

Microprocessor

Following GEC-Plessey's departure from the space business in 1998, ATMEL, Nantes (F) is the only European manufacturer of rad-tolerant microprocessors. The TSC695E, Sparc architecture at 25 MHz, was introduced in 2000. In the USA, Honeywell, BAE Systems and Sandia produce a line of onboard processors, the best known being the RISC 6000 family. In the US, the microprocessors are usually exclusive to a major aerospace company, which then markets products like full onboard computers or boards, rather than individual components. In Japan, a rad-tolerant version of the MIPS 64000 (e.g. a 64-bit machine, in comparison with the 32-bit Sparc and Power PC) has been produced.

Mass memory
From the hardware viewpoint, all countries have to adapt to the evolution of the COTS SDRAMs market. European units are now using mostly Samsung components, often with 3DPlus packaging. The potential advantage of having a rad-hard foundry available may not seem not so important, but the control part should ideally be manufactured using rad-hard ASICs.

3.3 Avionics Systems

The roadmap for rad-tolerant microprocessor is satisfactory, with the prospect of having a 100 MHz rad-tolerant microprocessor (LEON) in 2004. However, European industry took conservative options in the most recent planetary missions (Rosetta, Mars Express) with a higher mass and much lower computing performance than the equivalent US missions, by a factor of 20. Having said that, the research & development investment in advanced avionics systems is much higher than in the USA.

For onboard data networking, the *Onboard Computer and Data Systems Workshop* held at ESTEC in March 2001 decided to follow the route of MIL-STD-1553B instead of the European OBDH, to support European competitiveness in commercial markets. However, this standard is not the way of the future, especially for deep-space low-power missions. Although most of the European design currently relies on US components, Europe has the capability to be autonomous in procuring components for MIL-STD-1553B.

Alternative approaches based on industrial and international standards appear to be more suitable for those missions (I2C, IEEE 1394, CAN) and are being investigated by US and Europe (X2000 architecture of JPL, SMART-1 for ESA).

4 European Technology Programmes

In the past, ESA development of microprocessor and fault-tolerant computers and mass memory was performed through TRP and GSTP. However, few resources remained for the avionics system or for innovative ideas. Recently, the resources allocated to generic technologies (DMS, AOCS) in those programmes were reduced even further and left big gaps in the avionics toolbox (no off-the-shelf telemetry-telecommand chipset, no platform bus chipset). Furthermore, the lack of system activity like JPL's X2000 has resulted in an increasing disparity between the reference implementation architectures defined in the 1980s and the technology as actually implemented, which gave problems in some recent projects. A positive step has been taken by the Technology Programme of ESA's Science Directorate in preparation for BepiColombo. For extreme environments, CSEM (CH), CNM

(E) and Indra-Espacio (E) have performed assessments for martian, cometary and hot (>125ºC) environments. As a spin-off of this activity, a micro-camera using V-MCM technology, weighing less than 50 g and capable of operating from –140ºC to +40ºC, has been developed to fly on Mars Express/Beagle2 and SMART-1, while a derived version will fly on Rosetta's lander.

CNES has recently initiated a programme for microsats extensively using COTS elements. In micro-electronics, TRP and GSTP activities are looking at the feasibility of the 'rad-hard by design on commercial CMOS process' approach. The 'LEON' next-generation microprocessor, with a target performance of 100 MIPS, is being developed to be ready in 2004. The study of a non-volatile mass memory is also in the TRP planning. In GSP, related innovative activities are planned for wireless onboard communication and evolvable/reconfigurable hardware.

5 Justification and Rationale

Mission enabling and strategic value
Avionics are of strategic value and if highly miniaturised (within a system optimisation approach, as mentioned earlier), they are certainly an enabling technology (small probes, lander, return vehicle) with application to surface elements like rovers/robots.

Other space-related uses of the technology
If commercial programmes are not interested in developing advanced miniaturised avionics systems, they might be interested in using them off the shelf as they become available. For example, the current tendency is to build telecommunications spacecraft in 2 years, which demands off-the-shelf items because there is no time for technology development. In this respect, Aurora will act a technology driver of European space technology.

Terrestrial spin-offs
The interest of the space community in Europe's existing SOI-CMOS expertise may help this technology to become less confidential and to establish a commercial European capacity in an area that is occupied only by US companies (and IBM in particular). From the hardware point of view, terrestrial spin-offs might be found in high-profile applications. For example, the Mars-Moon micro-camera recurrent cost is of the order of €50 000, which is low for standard space hardware but high for public applications. The interest can only be for high-profile applications like an automatic station in Antarctica or high-altitude balloons. However, this is only one example. Having to solve multiple new problems at the scale of Solar System exploration will undoubtedly provide many opportunities for spin-offs – but it is not easy to predict precisely where and when.

Spin-offs can also be expected at the system level. Having worked out how to build highly autonomous systems with self-reconfiguration capabilities might open new perspectives for ground automation in harsh environmenta.

6 Technology Roadmap (Next 30 Years)

It is certain that future deep-space missions at a lower cost than currently possible will be enabled by highly miniaturised but highly reliable and capable micro-avionics systems. By providing the right instrumentation from the beginning, executing goal-oriented, high-level tasks with little assistance, missions launched after 2005 can have extended lifetimes if they have onboard preventive maintenance capabilities piloted by distributed and hierarchical fault-protection. Seeing the performance of Voyager, such missions could last 20 years or more as their software is updated from time to time. Of course, the onboard technology will be from 2005. From the first generation available in 2005+, some evolution will be possible without a 'technology revolution'. The system-on-a-chip concept will still be used, but allowing a bigger system, adding to the basic computing and commanding functions others such as telecommunication processing, power management, and storage for science data and program. Using CMOS or SOI-CMOS technology for a very large number of gates, techniques like massive parallelism on a chip will provide interesting and highly dependable solutions. They will also potentially prepare the engineering methods for the next generation of computing devices that will be available after the 2010/2020 timeframe, using new materials with quantum geometry being scaled at the molecular or atomic level. It will then be the era of the 'quantum information theory', but it is hard to predict today how and when such technologies will take over. Looking to the past, we can see that making accurate technology predictions for very far in the future is not easy. At the end of the 1970s, CCD bubble memories were presented as *the* solution for mass memories. They were all but forgotten 10 years later, as was the mid-1980s prediction of AsGa for digital ASICs.

However, computer science is more than the technology we use to implement it. For example, some of the ULSI or quantum computers of the future will draw on the work on cellular automata performed by the mathematician Von Neumann in 1950. It reemphasises the need to accompany the bottom-up technology-driven approach by a top-down approach providing a 'technology independence' at the system and services levels, allowing incremental evolution rather than a very costly permanent revolution. It also urges us to put a significant effort into CAE tools to support the technology evolution by providing automatic (to a large extent) paths from the functional and performance specifications down to the implementation level.

7 Technology Programme Proposal

Within the Aurora elements (spacecraft, vehicles, surface stations), it will be important to maximise the use of recurring avionics elements while making room for ESA's procurement policy. The development plan should concentrate on activities for which Aurora is the technology driver. The programme proposal presents a set of complementary activities tailored to Aurora's objectives, including inputs from recent and ongoing technology programs (TRP, GSTP, GSP, CTP). The 'Aurora Avionics' demonstrator should be developed to a level where it can be used for early flight demonstration (Sections 7.2, 7.3, 7.4).

7.1 SOI-CMOS Technology Validation (€1 million)

Assessment (Phase-1) and validation of the European potential in SOI-CMOS. The second phase should include the manufacture of test ASICs to be submitted to a wide range of environmental tests (temperature and radiation). If successful, SOI-CMOS will be widely used as part of the second generation of Aurora avionics systems.
Start: 2003 (duration: 3 years)
Phase-1: €300 000
Phase-2: €700 000

7.2 Aurora Avionics Architecture (€2.8 million)

Avionics system activity to provide a description of the Aurora avionics reference architecture, the services and application-level interfaces, including file systems and the Aurora avionics basic software as a reference 'open source' implementation. It should specify the hierarchical and distributed fault-protection to be implemented at avionics system level (to avoid the combinatorics explosion if all options appear in a single block in a central point or application software, making extensive testing impossible)

It will provide the detailed specifications of the avionics main building blocks that will be tested end-to-end in an integrated context (Aurora avionics demonstrator) before being released for the Phase-B/C/D of the first Aurora explorer missions.

The architecture should be open, using widely known industrial standards as far as possible and in compliance with ESA's procurement policy. It should specify the mechanical aspects (form factors, connectors) in addition to the services, protocols and electrical levels.

For the delivered hardware, the system demonstrator should be at the breadboard level, while critical elements (modules) such as the spacecraft controller should be delivered at the engineering model level, where individual critical components like 'system on a chip' are environmentally tested.

In order to reach these objectives, the activity should select, procure and adapt CAE tools to support hardware and software co-design, and the system engineering tools to support the efficient capture of mission and system requirements and their translations into unambiguous specifications. It should also propose an Aurora policy for COTS procurement at the programme level (central database, selection/validation procedures, procurement and storage).

This activity should run 2002-2006 as the system activity federating all the outputs of the other activities to provide an integrated system concept as presented in Sections 1 and 2.

Start: beginning 2002 (duration: 5 years)
Phase-1 (up to mid-2004): €800 000
Phase-2 (up to end-2006): €2 million

7.3 Aurora Avionics Main Building Blocks as a 'System on a Chip' (€1.7 million)

This covers two fundamental elements of the avionics, the spacecraft controller function (e.g. the embryo of any onboard computer and telemetry-telecommand system) and a standard user interface (data, power switching, control and monitoring, smart sensor interface) that can be implemented on the peripheral extension of the spacecraft controller or embedded within equipment/payload units. It should be implemented as a ''system on a chip' based on the functional and performance specifications provided by the Aurora avionics system activity.

The components are developed and manufactured in a rad-tolerant process that will be tested (temperature and radiation) before their integration into the avionics demonstrator. The corresponding synthesisable VHDL models of the implemented functions should be available for later implementation in a new process (bulk CMOS or SOI-CMOS) in further iteration of the technology during the second phase of the programme, if necessary.
Duration: 30 months (start: 3Q 2003; end: 2Q 2006)

7.4 Spacecraft Manager Software Kernel (€1.2 million)

While basic software is taken as an integrated and recurring part of the avionics, a significant part of the application software can also be considered to be recurrent within the context of the Aurora programme and should be supported autonomously. It concerns the highest layer of the spacecraft and mission management functions implemented on the avionics that can be defined independently of a given mission objective. It relates to the spacecraft management resources as well as to the processing of the contingencies and Failure Detection, Isolation & Recovery (FDIR) at platform level.

The spacecraft manager function should execute goal-oriented high-level tasks with very little intervention by the ground control centre, the process being proved as fail-op/fail-safe at the system level, in line with the fault-protection strategy (7.2).

Phase-1: specifications of the mission and spacecraft management function based on the reference Aurora avionics specified in the relevant activity and complemented by the identification of the core mission phases (Earth vicinity, cruise, Orbiter) of explorer missions.

Phase-2: implementation of the Aurora avionics spacecraft manager kernel and associated databases, integrated within a global-approach autonomous operations and recovery process. The delivered software should be tested as part of the Aurora avionics demonstrator.

Duration: 27 months (start: 4Q 2003; end: 2Q 2006)

7.5 Reconfigurable Hardware: Large-Scale Reprogrammable FPGAs (€1.2 million)

Phase-1: definition of a test case (functional and performance specification). Trade-off between a COTS-based design embedded in a rad-tolerant architecture (internal and external redundancy, rad-hard checker) or the development of a rad-tolerant FPGA process (e.g. with ATMEL) against the test case.
Phase-2: implementation of the selected concept, including manufacture of a support module and radiation-temperature test.
Duration: 2 years (start: 3Q 2003; end: 3Q 2005)

7.6 Reconfigurable System: Highly Dependable Computing on ULSIC (€800 000)

This activity aims to prepare a second phase (for implementation after 2005). It should identify the architectures for providing both performances and dependable solutions. It must make efficient use of the silicon at chip level using a small number of fully testable cores. It should then select one architecture approach and core and then provide a proof of concept, on a test case, through simulation and implementation of a subset on the last generation of FPGA.
Duration: 2 years (start: 3Q 2004; end: 3Q 2006)

7.7 Extreme Environment Technology Watch and Assessment (€800 000)

This activity aims at assessing the extreme environmental cases that can be met by the avionics elements, either during cruise, near-planet operations, landing or surface activities. It covers thermal, radiation, vibration and shock tolerances, plus atmospheric characteristics such as corrosion and dust.

Initially, it will follow a matrix approach identifying the technology candidates (bulk CMOS, SOI-CMOS, MCM, MCM-V, standard boards with SMT devices, passive components) and the extreme characteristics of possible missions for the next 10 years. It includes non-destructive and destructive testing, imposing the identified extreme conditions on representative ‘test vehicles’, and identification of assembly techniques (soldering, glue, metallisation, coating) to combat those extreme conditions. It is important to consider these items because they are as important as a costly microprocessor for the final reliability of the unit under the extreme conditions.
Duration: 27 months (start: 1Q 2004; end: 2Q 2006)

Annex 3

Data Processing and Communications Technologies

Annex 3 Contents

1 Introduction

Data processing and communications provide a key set of enabling technologies for Solar System exploration missions. This includes not only classical spacecraft control and monitoring (Annex 2) but also advanced data processing functions for which communication and onboard processing functions are becoming deeply interdependent. This is particularly the case for the four exploration phases outlined below. They are introduced here to support the definition of application domains and finally technological items to be developed, as detailed in Sections 3-5. These reference examples are not exhaustive but, rather, illustrate possible solutions to satsify *a priori* conflicting requirements related to full ground operability and a high level of onboard autonomy.

2 Exploration Phases and Related Specific Requirements

Globally, four sequential phases are to be considered for Aurora missions, irrespective of the specific targets. They correspond to:

— surface mapping with optical/RF instruments (in orbit);
— local environment characterisation by an array of surface stations (*in situ*);
— deployment of lander(s) with robotic support for samples *in situ* analysis or return;
— launch of a manned mission (on the basis of information gathered during the previous phases).

Major innovative functional requirements corresponding to these phases are detailed below.

2.1 Onboard Data Reduction and Interpretation

The very first step in the exploration of a planetary target is to fully characterise its environment, in order to select appropriate landing sites for following mission phases (e.g. for *in situ* sample analysis, collection and return). Surface mapping (2D and 3D) and atmospheric sounding are performed systematically. The typical resolution can vary from 100 m per pixel (global coverage) to 1 m per pixel or even less. With multi-spectral extensions, remote sensing instruments will generate huge amounts of data – equivalent to transmission data-rates higher by at least one or even two orders of magnitude than the available telemetry rate (even after enhancement). This leads to specific requirements for sophisticated onboard data-reduction techniques.

Data reduction is introduced here in a context less restrictive than data compression, opening the door to onboard data classification (for the sake of establishing transmission priorities) with respect to their intrinsic relevance. In this context, the following options could be considered:

— selective data compression with area-dependent compression and distortion ratios;
— detection of specific planetary surface structures for more detailed analysis (e.g. at higher resolution);
— identification of sudden changes in the environmental conditions with specific reporting (e.g. atmospheric changes).

2.2 *In situ* Data Acquisition by an Array of Disseminated Planetary Surface Environmental Stations

As a complement to surface mapping via remote sensing, *in situ* environmental data acquisition and subsequent data collection via an orbiter is a fundamental step for selecting potential landing sites. This phase is very demanding in terms of telecommunication support. The functional implications for data communication and processing are:

— geolocation of individual stations;
— intercommunication of stations;
— data collection mechanisms and interaction with a planetary orbiter.

Two operational modes should be considered: the basic one is a systematic interrogation of all stations; the second should be event-driven. This means that individual stations must have data-discrimination capabilities based on event signature identification.

In general, surface stations will have to sustain stringent environmental conditions (e.g. extreme temperatures and interference). Furthermore, miniaturisation and budget minimisation (power, mass) are fundamental.

2.3 Onboard Intelligence for Resource Optimisation and Risk Mitigation

A certain level of autonomy is mandatory for a lander and its robotic support, in addition to requirements imposed on surface stations. This leads to the development of onboard intelligence techniques and also applies to the spacecraft's cruise (manned or unmanned).

It is intrinsic in exploratory missions that the spacecraft's environment, although characterised *a priori*, contains residual unknown elements for which permanent monitoring is needed. This includes the optimisation of resources (e.g. energy and supplies) and permanent risk mitigation. Furthermore, during specific crucial mission phases (rendezvous or landing), even more information is necessary in order for the ground operators, crew or onboard computerised supervisor to make optimised decisions. In order to ensure the spacecraft's integrity, the monitoring system should be designed to:

— log and analyse sensor data in nominal situations;
— detect deviations (mid- and long-term) and anomalies (short- to very short-term);
— mitigate anomalies to filter out false alarms or force a switchover to safe modes;

— provide diagnostic information for recovery.

The main elements on which such systems can be built are:

— multi-sensor data collection, smart sensors;
— data fusion, soft thresholding, fuzzy logic;
— model identification and adaptive filtering;
— pattern recognition, signature analysis and anomaly detection.

One important requirement is system adaptability and the possibility of including new functions during the mission itself.

2.4 Teleoperation and Telepresence

Teleoperation and telepresence techniques as used presently in LEO manned missions cannot be translated directly to remote exploratory missions. Considering the inherent round-trip delay and, to a lower extent, the limited communication throughput, teleoperation and telepresence aspects must be significantly enhanced. Innovative concepts will have to be implemented and validated, using the most advanced technologies in this field. Of course, even if they represent a fundamental tool for robotic exploration, they are also very important for supporting the crew (e.g. telemedicine) and satisfying the public interest in exploration missions. Even with a limited interactivity, investigators and control operators must be given all the means for interacting properly with the mission scenario. (e.g. for robotic-element control and decision-based milestones). The following requirements must therefore be considered:

— visualisation/replay tools reflecting the data capture geometry with a high level of fidelity;
— high-quality digital imaging (spatial/temporal resolution);
— high-accuracy matching between imaging and ancillary data acquisition;
— seamless integration of model-based simulators and actual data databases;
— fulfilling the needs of Public Relations and Outreach.

3 Communication Strategy

The recent failures of NASA missions to Mars have shown that, for low-cost missions with little support, the least hiccough can cause unrecoverable and fatal consequences. With no *in situ* communication support infrastructure, no monitoring of the Mars lander was possible and no corrective action could be taken. Without monitoring data, no lesson could even be learned.

The large distance to Earth calls for a high level of autonomy for spacecraft visiting planets or asteroids and *in situ* supporting communication infrastructure. Transmission times do not allow ground operators to be in-the-loop, and small landers and penetrators do not have the resources (transmit power, antenna size, pointing capability) for direct links to Earth.

The communication infrastructure necessary for a programme of exploration includes a ground-based deep space network, data relays orbiting the target planet (Moon, Mars) in support of the landed elements, a local infrastructure on the planetary surface for communication between landed elements, and a localisation support system that may include orbiting spacecraft and ground-based beacons.

3.1 Deep Space Network

If Europe wants to embark upon an ambitious programme of exploration, the question of the terrestrial ground network support must be carefully analysed. Up to now, the limited number of deep space missions by ESA could be accommodated by NASA's Deep Space Network (DSN). Factors such as DSN's capacity and rental cost must be considered.

The current ESA stations of Perth (Australia) and Villafranca (E) have only S-band (now obsolete) and some limited X-band capabilities. The programme envisaged will require Ka-band (32 GHz) in the first stage, an extension to 37 GHz for the manned missions and optical communications for high-capacity transmissions.

Scenarios of manned missions to Mars consider using the Moon as an outpost. Several preparatory missions to the Moon could then be envisaged; the energy required to take off from the Moon towards Mars is far lower than that needed from Earth. International Telecommunication Union regulations do not allow the use of the 32 GHz band for near-Earth missions; missions to the Moon would be accommodated at 37 GHz. This band offers a 1 GHz bandwidth well-suited for very long base interferometry (VLBI).

3.2 Data Relays

There are at least two reasons that would justify the deployment of data-relay satellite(s) around the Moon and Mars to support their exploration. First, the local landers, rovers and penetrators will be limited in size and power and unable to communicate directly with Earth. Second, a data-relay satellite can ensure continuity of communication with the 'back' side of the planet.

The data-relay satellites constitute the communication backbone for the exploration of the Moon, Mars and other planets or asteroids. Being dedicated to communications, they will carry large antennas pointing to Earth, high-power amplifiers and highly sensitive receivers. They may collect the data from the small landed elements in a multiple access mode through fixed antennas or offer high-rate telemetry dumps for larger elements through electronically steerable antennas.

3.3 Local Infrastructure for *In Situ* Communications

For the automated probes visiting planets, a local radio infrastructure based on short-range radio links will be necessary. The use of low-frequency systems (typically 400 MHz) is a guarantee of simplicity, low cost, low mass and power, with fixed antennas. These radio links are limited in data-rate capability but they will be sufficient for a least the first generation. The band can also be used to collect lander and penetrator data from a low satellite. In the longer run, S-band (2 GHz) should be considered for higher rate transmissions. Manned missions to Mars require specific man-base or man-relay communication systems, providing voice/data communications, health monitoring and Internet-like access to databases.

3.4 *In situ* Geolocation

Spacecraft visiting Mars will need accurate means for autonomous (i.e. independent from terrestrial operators) localisation and navigation. Accuracy is required for precise landing and orbital rendezvous, as in sample return operations. This can be satisfied by a small set of Galileo/GPS-like satellites, complemented by fixed surface beacons. Data-relay satellites could provide a navigation service.

4 Communication Technology

4.1 Deep Space Network

The development of 32 GHz capabilities for deep space links is a must. An extension to 37 GHz for high-rate links with the Moon and manned missions and to optical links for missions to Mars, Europa and asteroids must be considered. The number of stations depends on the capacity forecast and the degree of autonomy that ESA wants to acquire, in conjunction with the capacity that NASA could offer.

The arraying of antennas may be an economic way of increasing the telemetry throughput (instead of deploying huge antennas). The deployment of VLBI capabilities (several ground sites coupled, time-synchronised) will be needed for accurately tracking the satellites from Earth.

4.2 Data Relays

Not much can be reused from the Artemis experience. A data-relay satellite around the Moon or Mars should be regenerative and operate at 32 or 37 GHz towards the Earth. It is likely that the missions launched beyond 2020 will have data capacities requiring optical links. Given that data relays have to be in place before the arrival of the spacecraft, work on optical communications should start at an early stage. Mass and power constraints will require the extensive use of miniaturisation.

4.3 *In situ* Communications Systems

The exploration infrastructure on the surface of the planet or in orbit requires compact, low-mass and low-power communication equipment. The extensive use of digital technology (software radio) would achieve the level of miniaturisation and power efficiency needed by energy- and mass-constrained penetrators, landers and rovers.

Some preliminary research & development work is under preparation for a system operating at 400 MHz, to serve BepiColombo. Within the CCSDS standard, ESA is working with NASA and other agencies on a standard for *in situ* communications that will allow optimum use of resources through extensive cross-support. An extension towards higher frequencies must be considered as a second step, given the relative data-rate limitations of the 400 MHz system.

4.4 *In situ* Geolocation

In principle, it is the intention to base geolocation systems on reuse of the Galileo/GPS technology. Obviously, a positioning system around Mars will significantly differ from Earth's equivalent, given that the satellites are limited to a few (against 24-30), complemented by some surface beacons. Reasonable performances could be reached with the use of more frequencies (ITU regulations do not apply there) or other techniques that remain to be investigated. No work has been done in ESA on this subject so far.

5 Payload Data Handling Techniques

5.1 Miniaturisation, Power and Mass Budget Minimisation

Miniaturisation is a recurrent requirement implied by the efficient implementation of data handling related to spacecraft command & control and payload data processing. The long-term goal is to make most of the current ground technology (e.g. VLSI devices, computers, networks and selected peripherals) available for space exploration. This includes in particular:

— micro-electronic system integration using the 'system on a chip' concept;
— the development of a giga ops/flops-class processor;
— systematic screening and evaluation of COTS solutions;
— optimised data-acquisition networks complying with harness-reduction objectives;
— operational power minimisation combined with idle/sleep mode management.

These technologies will have a generic impact on many subsystems and offer an extended scope, including instruments and sensors. A high inter-disciplinary horizontal harmonisation is required to avoid duplication of efforts.

Such technological developments are common to many future missions and therefore reflected in the Agency's TRP/GSTP programmes. Nevertheless, a significant participation in this effort must be undertaken by the Exploration programme for generic technologies. Specific requirements must be taken into account and particular criteria established for the evaluation of COTS technologies.

5.2 Smart Sensors & Instruments and Data Fusion

While the number and diversity of sensors is increasing in general, they will play an even more important role in the exploration missions because of the more uncertain targets they will find. Sensors and monitoring instruments should be developed with the following characteristics:

— unified interfaces able to operate at relatively high speed for raw data acquisition;
— embedded data-filtering (e.g. averaging, linear and non-linear filtering);
— if applicable, embedded signature analysis, spurious measurement cancellation or event detection and alarm generation.

This innovative field for space applications is not adequately covered in ESA's current technology development programmes (TRP/GSTP/ASTE). Much more effort should be dedicated to this field with fault detection, isolation & recovery (FDIR) aspects taken into account at the sensor level. Moreover, 'smart sensor' also denotes 'sensor reconfigurability', which underlines the need for high-performance onboard networks.

5.3 Networks and Data Flow Management

The management of data flow aboard the spacecraft is particularly important. As in a ground informatics infrastructure, onboard computers and networks should be seen as functional elements interconnected through a networked architecture. The following elements are crucial:

— fault-tolerant command and control computers;
— high-speed Digital Data Processing modules;
— mass-memory modules based in particular on non-volatile technologies;
— I/O modules with direct interfaces to smart sensors;
— network protocols, adapted file structure and transfer protocols.

Based on such elements, realtime requirements and offline processing could cohabit and share common resources. The distinction between these two types of applications is handled essentially by software applications.

The basis for onboard networks has been defined and is under development. This includes in particular high-speed digital links and packet routers. Nevertheless, very little effort has been dedicated so far to the application field. This relates to the lack of existing mission scenarios and the important effort needed for software modules development and integration. The contribution by the Exploration Initiative to this field should then be focused on integration and software aspects.

5.4 Adaptive and Distributed Processing

Based on the network architecture outlined in 5.3, processing tasks can be spread and managed according to the following principles:

— data-independent processing are handled by sensors' proximity digital electronics;
— low-level functions are executed by embedded processors;
— data fusion and interpretation are handled by supervising processor nodes;

— software module updating is integrated as far as possible in the nominal operational scheme;
— the software architecture allows dynamical insertion of new tasks with minimal impact on nominal operations.

Most of these features are common to ground systems and are already used in transportation systems (rail, aeronautics). The required step is to validate their use for long-term space missions. Considering the innovative nature of the concept, its application to payload data processing is judged to be adequate.

5.5 Onboard Intelligence

Universal artificial intelligence is a fairly old concept that has proved to be more difficult to achieve than initially expected. Nevertheless, application-specific artificial intelligence is realistic but still needs considerable investment and experimentation to achieve useful results (e.g. speech recognition, industrial artificial vision). For far-reaching objectives such as a totally automated car, the availability of human intelligence (i.e. the driver) and legal aspects have always counterbalanced the investment needed to develop and maintain fully automated systems.

Of course, these constraints are not relevant to space exploration, where the biological risks for humans could be so high that only an automated mission is conceivable. One benefit could be to implement an automated switchover to the survival mode in the case of a perceived hazard leading to an 'instinctive behaviour'. Nevertheless, should artificial intelligence be used, its scope of intervention should *a priori* be confined to situations where it cannot create hazard. In the case of manned missions, artificial intelligence is necessary as a support for event analysis and decision-making, but it is clear that a human decision (either onboard or on the ground) will always be preferred.

The approach recommended in the frame of the exploration initiative is four fold:

— study and evaluation of advanced computing techniques such as neural networks, fuzzy logic, classification systems and genetic algorithms;
— development of the necessary building blocks;
— integration of data fusion, learning capabilities, expert systems in a test bench;
— benchmarking during mission simulations between human decisions (operators and/or crew members) and fully-autonomous/assisted decisions.

The studies and developments towards alternative processing techniques for onboard intelligence must be initiated at the very beginning of the exploration programme because their level of maturity is low for space applications.

As far as pure technological items are concerned, emphasis should be placed on the availability of high-performance computers, database management systems and flexible non-volatile mass memories.

Table 1. Technology Goals and the Current Situation.

	Goal to be Reached by the Technology	European Position on Mastering the Technology	Situation in USA	Situation in Russia, Japan, other	Justification for European Activity
Telecommunications					
Deep Space Network	European network capable of supporting European universe exploration initiative. NASA Deep Space Network reserved as backup or for peak demands	32/37 GHz Technology not available in Europe (large antenna, HPA, …)	Partly available	Not available	Required for the programme
Data Relays	Telecommunication support to the programme	To be developed	Under study	n.a.	Dependen‹
In Situ Communications Systems	Inherent part of the programme	To be developed	Partly available		
In Situ Geo-location	Inherent part of the programme	To be developed	Under study		
Data Processing					
Miniaturisation	System on a Chip based on libraries of IP blocks	Concepts are in place for commercial application, need to be transferred on Rad-Tol Silicon processes	Strong and well advanced, US leads the microelectronics sector	Strong but essentially for Consumer Electronics	Generic technology, required by almost all space programmes
Smart sensors	Sensors with embedded conditioning electronics and first-level digital processing (e.g. filtering)	Technology well mastered in Europe for automotive and industrial applications, needs to be transferred on Rad-Tol technolgies	TBI		
Networks	Fully integrated onboard network with packet routing capability	Well advanced, SpaceWire Links in development and currently standardised. Rad-Tol controllers exist	At investigation level	TBI	
Mass Memories	Compact non-volatile memories with standard interfaces and integrated support for file system	Volatile Mass Memory Units have been developed in Europe	Same level as in Europe		
Adaptive & Distributed Processing	Inherent part of the programme	Emerging	TBI		
Onboard Intelligence	Inherent part of the programme	To be developed	TBI		
Global S/W Lifecycle Management	Inherent part of the programme	Emerging	TBI		

TBI: to be investigated

Table 2a. Past and Current Activities in Telecommunications and Data Processing.

	Past TRP, GSTP, GSP, ASTE Activity	Current TRP, GSTP, GSP, ASTE Activity	European Companies with Capability
Telecommunications			
Deep Space Network		X-band 35m antenna in Perth	Alcatel, Astrium
Data Relays	-	-	Alcatel, Astrium, Alespazio
In Situ Communications Systems	Preliminary R&D for BepiColombo and in the frame of CCSDS	High-frequency extension needed	Alcatel, Astrium, Alespazio
In Situ Geolocation	-	-	Alcatel, Laben, Astrium
Data Processing			
Miniaturisation			Astrium SAS (F), 3D+ (F), ATMEL (F)
Smart sensors	Highly integrated micro-cameras, thermistors with digital interface, etc		CSEM (CH)
Networks	High-speed links in development since 1995 Modelisation of the Spacewire protocol and router in SDL	SpaceWire controllers and Routers in development. TOPNET Initiative launched.	Astrium GmbH, NLR (NL), UoD (UK), Autrian Aerospace (A), Telelogic (F)
Mass Memories	PALASIM Mass Memories	High Capacity Memory Buffers (32-128 Gbit per module). File Management Systems	Astrium GmbH (D), IDA (D)
Adaptive & Distributed Processing	R&D contract with SpaceBel for PC-based testbench	TRP with AXLOG for optimised distribution TRP compact computer core software architecture for OBSSDS	Spacebel (B), Axlog (F)

5.6 Global Software Lifecycle Management

The concepts introduced in this section cover essentially the needs of payload data-processing systems and not the critical ones of the avionics subsystems.

Though the capability/cost ratio increases rapidly for hardware and micro-electronics devices (following Moore's law), software development does not follow this trend at the same pace. This introduces software activities quite systematically in the critical path for embedded systems development. The origin of the gap is partly due to the requested high degree of flexibility and to the complexity (an intrinsic property of software), but also to a lack of rationalisation in software development methodology. This applies especially to the space sector, which uses a conservative approach. For instance, Object Oriented Programming techniques are scarcely used because they are thought to be too expensive in terms of test and system resources (processing capacity, memory budgets, etc.), though these resources are not limitations any more in advanced payload data-processing systems. Moreover, even if

Table 2b. Past and Current Activities in Onboard Intelligence.

	Past TRP, GSTP, GSP, ASTE Activity	Current TRP, GSTP, GSP, ASTE Activity	European Companies with Capability
Object-oriented languages	HOORA, the method for embedded software using UML Port of gnat and Raven (Ada95 object oriented) on ERC32 OOL Object Oriented Languages study	- AOCS Framework in Java - TRP Internet & Interoperable Technology - TRP Component Oriented - Development Techniques - TRP Tools for the production of O/BSW running on new generation computers - GSTP Reliable onboard compiler and operating systems	E2S (B), Konstanz University (D) UPM (E), ACTE (F), Aonix (UK) Astrium gmbh (D)
Multi-threaded task management	ORK, open source Ravenscar Kernel on ERC32		UPM (E)
4th generation language	DDV, use of SDL for avionic modellisation	- Use of ESTEREL to model onboard software - GSTP Formal Specification and Rapid Prototyping of realtime systems	Astrium (F), Verimag (F), Esterel Technology (F), Universite de Rennes (F), Telelogic (Sweden)
MMI		ODF, tool for astronaut procedure authoring	Astrium GmbH (D)
Autocode	ESTEC internal laboratory work on MatrixX	TRP Automatic Code Generation	
Artificial Intelligence			AnimatLab, Laboratoire d'analyse et d'architecture des systèmes, Université Paris VIII - Laboratoire d'intelligence artificielle, INRIA, Laboratoire d''études en intelligence naturelle et artificielle (LEINA), Artificial Intelligence Applications Institute, Biological Computation Project, Univ. of Alberta, German Research Center for AI, IRIDIA (Université Libre de Bruxelles), Staffordshire University AI Research, Vrije Universiteit Amsterdam Department of AI

multi-threaded task management is feared because of its lack of determinism, it might still be an efficient solution when restricted to payload data-processing functions. Similarly, fourth-generation languages have not even been tested for onboard applications despite their adequacy for handling Man-Machine Interfaces. Along the same line, Automatic Code Generation is still a dream without sufficient investment to make it suitable for space. Overall, it is believed that all of these techniques are useful tools for developing systems for manned and unmanned Solar System exploration. The justifications related to flexibility and development costs are made below.

Table 3. The Required Budget for the Technology Preparation Development Activities in 2002-2006.

	Present Standpoint and Goal	Intermediate Development Steps	Necessary Budget	Other Space-Related Use of Technology	Terrestrial Spin-Off
Telecommunication					
Deep Space Network			1.0 M€		
Data Relays			1.0 M€		
In Situ Communications Systems	Preliminary R&D for BepiColombo and in the frame of CCSDS	High-frequency extension needed	1.4 M€		
In Situ Geolocation			1.3 M€		
Data Processing					
Miniaturisation			0.7 M€	Micro-Avionics	
Smart sensors			0.5 M€		
Networks			0.5 M€		
Mass Memories			0.8 M€		
Adaptive & Distributed Processing	Development of individual modules and network skeleton	Fully integrated test bench, TOPNET compliant	1.0 M€	In all missions.	
Onboard Intelligence	General studies	Integrated demonstrator for human/artificial intelligence benchmarking	1.2 M€	In all missions, even in ground software dev.	Transport and automation
Global Software Lifecycle Management	Evaluation of isolated tools and software workshops	Generation of compact and proved software with dynamic update capability. Validation of TaskWare concept	1.2 M€	In all missions, even in ground software dev.	Any software development, specially embedded software

5.6.1 Flexibility

The exploration systems will be so complex that the flexibility offered by software (during the development phase and the mission itself) will play a very important role. As a consequence, software tasks will be widely distributed on embedded micro-controllers, general-purpose processors and dedicated co-processors. These processors should be seen as a large heterogeneous multi-processor system. At an even broader level, one should take into account large-scale systems based on tens or hundreds of small meteorological stations, planetary-rovers/stations/orbiters/relay satellite systems and multi-module manned spacecraft working cooperatively.

Such software systems cannot be developed in one go, first of all because modules (orbiters, meteo stations, rovers) will not be deployed all together.

Secondly, software evolution (not only basic maintenance) will be part of the software's lifetime. Software will have to adapt to changing configurations at module, subsystem or system level. It will have to be patched *in situ* to accommodate new algorithms, new services, new interfaces and communication channels, without being suspended because delivery of minimal services is required. This implies the use of advanced Operating Systems and Middleware, allowing not only task distribution and planning but also interactive task management (patch, creation, addition, suspension and replacement) and self-maintenance (auto-rejuvenation, diagnostic of nodes and system-level garbage collector). Such a concept will be called TaskWare. TaskWare support tools must be developed to achieve easy management of tasks and services at the large-scale system level. This is not covered by presently planned TRP and GSTP activities.

5.6.2 Design and Maintenance Costs

The software's complexity means that development costs will be significant. This should lead to a high level of concern and generate a high burden on the Aurora programme. One way of mastering these costs is to invest *a priori* part of the budget in the definition and the development of a fully-fledged software development system customised for exploration missions. This is driven by the necessity to produce and maintain huge amounts of code in a cost-effective manner. Object-oriented languages, system description languages and fourth generation languages are emerging tools available for industrial applications, but they need to be improved, validated and tailored to space applications.

The developments towards global software lifecycle management techniques must be initiated at the very beginning of the exploration programme because they are enabling technologies for complex missions.

Annex 4

Entry, Descent and Landing

Annex 4 Contents

1 Introduction

This Annex covers aspects of atmospheric flight for missions involving flyby, entry or orbit around a planet surrounded by an significant atmosphere. For robotic missions, it concerns Saturn's satellite Titan and all the planets except Mercury. For manned missions, only Mars and Earth are considered here.

An atmosphere provides the possibility of using aerodynamic forces – lift and drag – to correct the flight path of a spacecraft. They can deflect its trajectory, change its orbital characteristics (aerobraking, aero-gravity assist, aeroassisted maneuvres), ensure its capture in orbit (aerocapture), or even decelerate it to set up a landing (entry), while providing important propellant savings.

Aerobraking uses atmospheric drag to decrease a spacecraft's orbital velocity in order to modify its orbit. The values of ΔV above which aerobraking is beneficial with respect to propulsive braking are plotted in Fig. A1, for different values of the mass fraction (λab) of the aerobraking system. An aerobraking system representing 10% of the spacecraft mass is already beneficial for a deceleration as small as 500 m/s.

Aerocapture is an extreme case of aerobraking. The spacecraft's initial velocity (higher than the planet's escape velocity) is reduced during the flyby to an orbital velocity, and the spacecraft is captured into a closed trajectory around the planet. Aerodynamic efficiency (lift) of the spacecraft relieves the navigation accuracy requirements. In the first phase, lift is oriented towards the centre of the planet to avoid skipping out of the atmosphere into space. Roll manoeuvres follow, to limit heating and avoid entry. A reduction of a few km/s ensures capture. Aerocapture offers great benefits over any form of propulsive boost, as soon as the spacecraft mass is large enough to carry aerobraking systems (GNC, heatshield, control thrusters, propellant). This is particularly true for Mars or Venus aerocapture of sample return spacecraft, and of Mars and Earth aerocapture for manned missions.

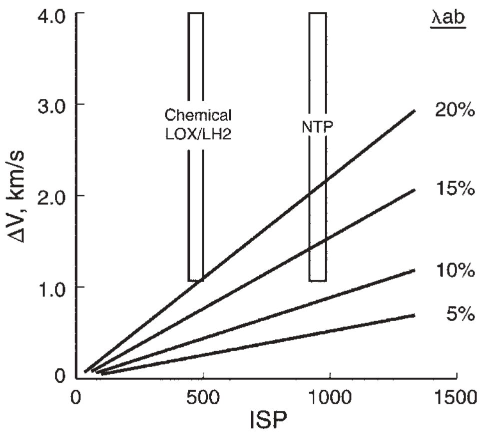


Fig. A4.1: Aerobraking versus propulsive braking. (From E.B. Pritchard, 'Mars: Past, Present and Future', *Progress in Astronautics and Aeronautics*, vol. 145, AIAA, 1992.)

For manned missions, deconditioned crews cannot sustain high deceleration levels during entry. Direct high-speed Earth entry implies high decelerations. One consequence is the need for orbital rendezvous on return from Mars, and establishing an Earth orbit is best achieved by aerocapture. However, even orbital entry leads to relatively high *g*-loads (more than 7 *g*) for ballistic entries. An advanced Crew Return Vehicle with adequate aerodynamic efficiency (lift) can achieve a controlled low-*g* (down to less than 3 *g*). In addition, accurate landing and higher levels of reliability are required for manned missions, in particular at the explored planet.

Finally, payload masses can be significantly higher for manned than for robotic missions, and some technologies could become competitive by offering more safety margins for less mass or being cost-effective. For example, reusability could be envisaged for Crew Return Vehicles. In addition, higher reliability is required. This has an impact on the design and verification of all subsystems.

The presence of an atmosphere allows consideration of airborne transportation of instruments or humans, including balloons (including aerobots),

Table A4.1: Entry, Descent and Landing Technologies.

Technology	Aerocapture/ aerobraking	High-speed Reentry	Light ballistic entry & descent systems	Light guided & controlled entry systems
Ablative materials		++		
Thermal cycling	++			
Air/CO_2/H_2/CH_4 chemical kinetics + gas-surface interaction	++	++	+	
Ionised flows, ablation effects		++		
Plasma radiation	++	++	+	
Wake flows	++			
Dynamic stability			+	+
Rarefied and transitional flows	++			
Turbulent flows		+		
Jet/flow interaction				+
Landing systems		++	+	+
Guidance/Navigation/Control	++			++
Atmospheric models	++			
Flight instruments	++	++	++	++
Ground testing & instrumentation	+	++	+	
Computational Fluid Dynamics	+	++	+	++
Inflatable/deployable structures	++		++	+
Advanced heatshield concepts			++	++
Optimal shape definition	++			++

aircraft, autogyros, helicopters, kites and parascending. Such vehicles need to be designed specifically for the low-density carbon dioxide atmosphere of Mars, or the high-pressure and high-temperature atmosphere of Venus. Only balloons and aerobots seem appropriate candidates for early development, in the timeframe 2001-2005.

Soft-landing can be performed in all cases by propulsive means. This technology is discussed in Annex 8. However, the presence of an atmosphere offers additional options, such as inflatable decelerators, parachutes, parafoils or even rotating or fixed wings. Retrorockets or landing devices absorb the remaining kinetic energy at impact with the surface.

A number of technologies are discussed further at the end of this Annex. However, a basic requirement for using the technologies in the exploration programme is their validation in low-cost demonstration missions. This is clearly required to validate advanced concepts, or even conventional ones beyond their nominal range of application, but it is also needed to assess the safety and reliability of critical elements of a costly mission. In particular, aerocapture and high-speed Earth entry (above the Earth-escape velocity of 11.2 km/s) require flight demonstrations. The availability of low-cost flight opportunities makes flight demonstrations even more attractive. The robotic exploration of the Solar System will involve landers for scientific exploration, but also for technological demonstration.

Before sending humans to a planet or moon, sample return missions must validate all the segments of the manned mission. For these unmanned flights, a lightweight (20-30 kg) Earth Entry Vehicle must be developed able to perform entry at 12-16 km/s.

Several technologies need to be considered for this Annex, related to:
- multidisciplinary optimisation;
- aerothermodynamic predictions and verifications; in particular, databases and methods for the prediction of radiative and convective heat flux associated with high-speed Earth and Mars entries;
- aerodynamic characterisation for complex shapes, forces and moments, stability in all flight regimes, low-Reynolds flight properties for atmospheric vehicles;
- flight measurement techniques and flight reconstruction. Flight instruments are also used by the GNC system;
- advanced thermal protection system design and verification. In particular, requirements from accommodation, mass availability, safety and possible thermal cycling associated with aerocapture and aerobraking lead to development requirements in light and efficient ablative materials, inflatable structures or foldable wings, or even reusable concepts. Advanced concepts making use of electromagnetic or radiative interactions with the flow could provide additional guidance capabilities as well as decreased heat loads on future vehicles. For manned missions, the readiness of ground test facilities needs proper assessment, both for Mars and Earth entries;

— Guidance Navigation & Control (GNC) constraints associated with accurate landing or manoeuvres (Annex1);
— shock attenuation systems, in particular for sample return missions, when passive, decelerator-less systems are considered;
— the propulsion aspects of ascent and descent vehicles are examined in Annex 8;
— modelling of the atmosphere and of the surface of the planet.

2 Heritage and Status

ESA has participated in a number of projects, some in cooperation with NASA or Rosaviakosmos:

— for controlled Earth entries: Atmospheric Reentry Demonstrator (ARD) and X-38 (NASA);
— for unguided ballistic Earth entries: the German Mirka capsule and ESA's Inflatable Reentry and Descent Technology demonstrators: IRDT(2000), IRDT2(2001) co-funded by the European Commission and developed in cooperation with the Babakin Space Centre in Russia;
— for planetary (unguided) entries: Huygens, launched with the Cassini spacecraft in 1997, will land on Titan in 2004; Beagle2 will be launched in 2003 with Mars Express to land on Mars;
— planetary probes under development within national programmes: Netlanders (CNES), Mars Sample Return Orbiter (CNES);
— BepiColombo includes a Mercury lander, to be launched after 2009.

In addition, military developments of entry vehicles have been performed in the UK and France.

Various feasibility studies have also been performed:

— for comet sample return: Rosetta/CNSR in 1990 studied a comet lander, and an Earth Return capsule;
— several studies were dedicated to Mars between 1992 and 1998: Marsnet/Intermarsnet/Mars Express;
— for ESA's Mercury cornerstone mission, a Venus probe was proposed taking advantage of a Venus flyby;
— Venus Sample Return/Mercury Sample Return missions were studied in 1998-99.

3 Technology

Significant technological progress was achieved in ESA's Hermes and follow-up Manned Spaceflight Technology Programme, leading to new facilities, analysis methods, concepts and materials. This progress emphasised life support and Earth entry vehicles but could easily be extended to other planetary entries. In particular, facilities and tools have started to be adapted for Titan, Mars, Venus atmosphere and extreme Earth reentry conditions characteristic of super-orbital velocities. In particular, the following technological research programmes have been pursued:

— aerochemistry TRP: databases for Earth and Mars;
— ISTC 36, ISTC 1549: co-funded by the European Commission, technology cooperation with Russia in Mars and Earth entry aerothermodynamics;
— various TRPs on contamination, lightweight heatshields, landing systems, etc.;
— PASDA, parachute analysis;
— AAS aerodynamic analysis system;
— tether study (TSE): includes an Earth entry minicapsule (20 kg) currently under investigation;
— martian climate model;
— aerocapture/aerobraking (GSP).

Industrial capabilities have been enhanced by:

— the construction of new plasma test facilities (VKI's Plasmatron in Belgium, SCIROCCO Plasma Wind Tunnel in Italy) or the upgrading of existing ones (SIMOUN in France, L3K in Germany);
— commissioning of new wind tunnels, from subsonic up to hypersonic speeds (e.g. ONERA's F4 in France, DLR's HEG in Germany);
— new measurement techniques have been introduced and Computational Fluid Dynamics (CFD) further developed, validated and more widely used.

Europe has good capabilities for Earth and planetary entry missions. Large companies (EADS, Astrium, Alenia, Alcatel) but also smaller or less specialised ones (Dassault, FGE) can lead or contribute to the development of entry probes. For significant contributions, SNECMA in France and MAN in Germany are examples of available expertise. However, Western Europe has never performed either Earth entries at super-orbital speeds or aerocapture manoeuvres, but a number of military technologies provide a good starting point. Europe also needs to progress in manned vehicles, flight instrumentation, accurate prediction of aerothermal environment (in particular radiative fluxes), accurate landing and advanced heatshields. The development of a manned vehicle, for which European experience is limited, requires significantly longer programmes than for robotic missions. Russia and the US have a technology base that encompasses all aspects of exploration missions. Japan has embarked on a technology programme, to develop the HOPE space shuttle. After flying a reentry capsule (OREX) and a low-speed aircraft covering the subsonic regime (ALFLEX), a lifting body (HYFLEX) protected by an advanced ceramic heatshield has successfully performed a suborbital entry. However, the programme has been slowed.

More intense technology cooperation, especially with Russia, would allow the reduction of development costs, the transfer or acquisition of the missing technologies and the building of a frame for an international programme.

4 Justification

Aerocapture, aerobraking and entry, descent and landing technologies are unavoidable for a number of robotic and for all human missions. Space spin-offs are mainly related to reusable launchers. Terrestrial spin-offs of entry technologies include plasma processing (including waste processing), high-temperature protective materials and high-speed transportation systems, safety systems (airbags for aircraft, rescue and recovery systems, etc.) and advanced instrumentation.

5 Technology Roadmap

The reference exploration phases are highlighted below in italics.

2001-2005

2005: *in situ resource utilisation/life support (ground demonstration)*
autonomous rendezvous & docking
start International Space Station Columbus/ATV exploitation

— advance research on new concepts for heatshields, on landing systems, on aerothermal analysis and flight instrumentation, on life support, on accurate landings;
— perform demonstration flights for high-speed Earth entry and for Earth aerocapture (compatibility with CNES sample return mission demonstration, in 2007);
— perform feasibility studies for Moon and Mars sample return missions, and for Moon and Mars manned missions, in order to prepare requirements for the development of corresponding technology and facilities, and to assess the benefits of promising technologies.

2005-2010

2007: *CNES Mars sample return technology demonstration mission*
2010: *soft landing (Moon, Mars, asteroids)*
Interplanetary Transfer Stage
Europa Orbiter
in situ characterisation/resource utilisation test (asteroids, Moon, Mars)
in situ exobiology (Mars)
communications network (Mars)

— perform flight demonstration of Mars aerocapture (could be associated with a scientific mission) and Mars accurate landing. Once knowledge of the planet increases, more accurate landings and surface mobility will be required;
— initiate development and test of a Crew Transport Vehicle to and from Earth orbit (orbital rendezvous is preferred to direct entry for human missions to Moon or Mars). This vehicle needs to be ready by 2020;
— develop and test advanced miniature Earth Return Vehicle demonstrators;

— perform flight test of lightweight ballistic entry and descent systems implementing advanced heatshield technologies;
— study Earth and Mars aerocapture for a manned vehicle.

2010-2015

2015: *robotic precursor missions*
Europa lander
sample return (Mars, asteroids)
knowledge base on humans 'living in space'

— perform Moon sample return mission as precursor to operational manned Moon mission (2020);
— validate Crew Transfer Vehicle and start its operational use: this vehicle is needed for the 2020 operational Moon mission;
— perform flight test of lightweight guided and controlled entry and descent systems. These systems are required for the robotic exploration of Mars, and to preparate for manned missions;
— validate Mars aerocapture for a manned vehicle.

2015-2020

2020 *operational Moon mission (in situ resources utilisation & life support)*
man-rated soft-landing (Moon)
robotic planetary outpost/deep drilling
planetary 'Internet' capability (planetary relay satellites)
in situ resources utilisation (asteroids, Moon, Mars)
closed-cycle life support

— perform Mars sample return mission;
— studies of man-rated Mars entry vehicle initiated, for availability in 2030.

2020-2025

2025: *infrastructure operational on Mars surface*
man-rated Interplanetary Transfer Vehicles
man-rated soft-landing (Mars)

— development and robotic flight demonstration of man-rated Mars entry vehicle.

2030

manned mission to Mars
human mobility on planetary surface

6 Aerothermodynamics of Hypersonic Entry Vehicles

During entry, a spacecraft flies at several km/s. The surrounding flow is heated (typically >10 000K) by a strong shockwave formed in front of the vehicle. This heated flow is dissociated, ionised and emitting thermal radiation. Its degrees of freedom (vibration, rotation and electronic excitation) are excited. All these processes are out of equilibrium and are governed by complex kinetics. They cannot be perfectly simulated on the ground, and require both theoretical and experimental investigations. The design of the thermal protection system of an entry vehicle requires an accurate knowledge of the aerothermal environment during entry, and also of the interaction between the flow and the vehicle's surface.

ESA has performed initial studies into aerochemistry and plasma radiation within the TRP. In martian aerochemistry, chemical and vibrational kinetic schemes have been proposed, but need further assessment and extension to higher temperatures and conditions where ionisation occurs. Gas-surface interaction has been studied for catalytic properties of ceramic coatings, and initial research on ablation has been performed in solar furnaces.

For radiation, Huygens was developed using an old version of the US NEQAIR code for evaluating non-equilibrium radiative fluxes. ESA then funded the initial development of the PARADE radiation code, for atomic species. The second phase of development, for molecular species and code validation, have still to be funded. PARADE is also being used in studies of the Mars sample return mission.

The US and Russia have extensive experience of aerochemistry activities. NASA has continued to pursue them since Apollo at a rather high level of effort. Similarly, radiation continues to be thoroughly studied: NEQAIR and its RADMOD Russian counterpart are the most advanced codes. Funding for aerochemistry and radiation should be at a level of €200 000 each year over 2001-2005, for a programme focused on high-speed Earth and Mars entries.

7 Advanced Heatshields

7.1 Introduction

Heatshields represent a considerable mass fraction of an entry vehicle. Inflatable shields with control capabilities, electromagnetic shields and reusable shields able to withstand thermal cycling could provide not only mass savings, but also new mission opportunities such as aerocapture and entry by a single shield, guided entries with axi-symmetric shapes, and manoeuvres. In addition, other technologies need to be explored, such as drag reduction by injecting energy upstream of the vehicle.

7.2 Technology Item Description

The goal is to offer new reliable technologies for the thermal protection system.

7.3 Status

Some of the technologies have been investigated experimentally in the US and Russia. A large effort in the US is underway into drag-reduction techniques, which would also benefit future launchers.

7.4 European Technology Programmes

Europe has begun theoretical investigations (Astrium) into electromagnetic shields within the Agency's GSP programme.

7.5 Justification and Rationale

Reducing drag, improving the thermal environment, and saving mass would directly benefit future reusable launchers. Terrestrial spin-offs lie mostly in high-speed transportation systems.

7.6 Technology Roadmap (Next 30 Years)

The technology roadmap remains to be determined.

7.7 Technology Programme Proposal

The first step is an evaluation of the technologies in terms of cost, performance and feasibility issues (2002). Then, promising concepts should lead to the design, construction and test of prototypes (2003-2005). Selected concepts should then be flight-tested in 2005-2010, for them to be available for future human and robotic missions. The cost of the first phase is of the order of €200 000, and the second phase €400 000 per year.

8 High-Speed Entry Demonstrators

Return from Mars or other planets involves very high-speed Earth entry (11 km/s Moon, 14-16 km/s Mars), compared with orbital entry (< 8 km/s). Sample return missions require miniaturised, probably passive probes, weighing around 20 kg. Such missions are clearly required as precursors to manned planetary missions. NASA has already flown capsules for extremely high-speed entry (Apollo, Galileo and Pioneer Venus), while Russia has flown capsules for Moon sample return, and Venus entry. Such expertise is absent in Europe, except for some TRP developments in support of Rosetta/Comet Nucleus Sample Return (CNSR) preparation, and for military warhead technology.

A technology flight demonstration for a 30-40 kg capsule is a necessary first step, and could provide an option for future enhancements to on-going national programmes. In parallel, a research program should develop new heatshield materials or concepts, allowing further reductions of mass. Lightweight ceramic ablators would make an important contribution.

Promising SEPcore-like concepts have been studied within Rosetta/CNSR, and military warhead technology is potentially applicable; a mission and system study is required, which would also validate the sample conditioning and recovery procedure for sample return missions. In addition, innovative mission analysis options could be introduced that may be required for future human exploration. For example, making use of gravity-assist at Libration points to bounce back to Earth and enter against atmospheric rotation is a promising concept.

The cost for a high-speed demonstrator would be about €30 million, including bus and launch, with Russian participation, after a €400 000 Phase-A study. Development would require 2-3 years, which should begin now in order to be useful for and in phase with the CNES Mars sample return demonstration mission in 2007.

9 Aerocapture Demonstrator

This technology is needed for manned planetary missions, and would benefit purely scientific missions. Missions to Mars and Venus, for example, could use the technology even for an orbiter. Missions to Europa could take advantage of aerobraking at Jupiter, and those to Phobos from Mars aerobraking. Before operational introduction, aerocapture and aerobraking require technology flight demonstration.

The US has thoroughly studied aeromanoeuvres, and particularly aerobraking and aerocapture. NASA performed aerobraking with Magellan (Venus) and Mars Global Surveyor but has never used aerocapture. Russia used aerocapture in 1968 for the Zond-2 robotic mission returning from a lunar flyby. Aerobraking capabilities are included in ESA's Mars Express, but its baseline does not make use of them. There is no previous West-European experience of aerocapture, but it is being developed at CNES for their Mars sample return Orbiter. A GSP study has been performed on the aerothermodynamic aspects. The first step in developing this technology is a mission and system study (elements exist in Mercury and Venus sample return studies) into a low-cost flight demonstration.

An Earth aerocapture demonstration is a low-cost initial step to demonstrate some elements of the technology before performing Mars aerocapture. The major missing element is the influence of navigation inaccuracy at Mars, and the uncertainties in our knowledge of the martian atmosphere. The Earth mission could be performed with Russian participation, within 2-3 years, at a probable total cost below €30 million for a small vehicle (€10 mission from Russia), after a €400 000 Phase-A study. The mission could be shared with a demonstration flight of high-speed Earth entry.

The cost of a Mars technology mission is estimated at more than €50 million (€20 million from Russia). Good synergy with national programmes is achieved if the Earth mission is performed before 2005.

10 Landing and Lander Technology

10.1 Introduction

Ultimately, the exploration of the Solar System and particularly of bodies and planets such as the Moon, Mars and various asteroids implies safely landing manned spacecraft on the targets and safe returns to Earth of the crews. In order to achieve this, a preparatory programme aimed at landing robotic payloads on these bodies is necessary to pave the way for the manned exploration. Among the exploratory missions, sample return calls for landing the robotic payloads on the target and the samples on Earth.

10.2 Technology Item Description

10.2.1 Landers

Landers include small and medium robotic vehicles as well as large manned capsules and spacecraft. The technology is strongly related to the environment at the target body to explore, e.g. the absence of an atmosphere dictates an all-propulsive descent, which is energetically costly and complex but allows complete control of the landing process.

Small scientific planetary or cometary landers do not differ much from conventional satellites or payloads. They are often considered as a payload and can be developed by Scientific Institutes with some industrial support. The main problems associated with them are the limited resources they offer to the scientific payload, which requires a very high level of integration of the payload with the vehicle. They are also characterised by their high autonomy and they usually rely on an orbiting companion to relay data to the Earth.

Large vehicles are also required for technology/robotic missions to prepare the infrastructure for the following manned missions. The payload capability has to be dramatically increased and very efficient structural concepts have to be devised, similar to or better than those currently used in launch vehicle design.

Finally, large interplanetary shuttles are necessary to bring crews from orbit to the outpost. The technology is completely different from that of robotic landers because it needs to be man-rated and, for the return, reusable.

10.2.2 Landing Systems

Depending on the descent conditions and the payload requirements, a wide range of landing systems can be considered. They include, ranked by ascending complexity:

- penetrators suitable only for a certain class of scientific payloads;
- passive shock-alleviation devices, including crushable structures and inflatable devices that provide a large deployed volume compared with the allowable launch volume;
- reusable landing gear suited to landing large structures.

10.3 Status

Europe's first planetary lander is the Huygens Probe that is on its way to Titan. The second is the Rosetta cometary lander that will be launched on its long journey in 2003. Several developments were pursued in scientific Mars exploration, including NetLander and Beagle2, the last scheduled to fly on ESA's Mars Express. France might also fly some landers as a contribution to the NASA Mars programme.

All major European space companies have the capability to develop robotic planetary landers. For more complex systems, including manned vehicles, only the few already involved in space infrastructure (Astrium GmbH, Astrium France, Alenia Spazio, EADS Launchers) have the required capability.

So far, only NASA has landed crews on a celestial body (the six Apollo lunar landings of 1969-72). NASA has also landed robotic payloads on the Moon, Mars and Venus. Russia's planetary exploration programmes were exclusively robotic (Moon, Venus; the manned lunar programme was cancelled in 1974) and were the result of a robust approach that included onboard autonomy. Little is known about Japan's projects, but they are expected to launch several lunar penetrators.

10.4 European Technology Programmes

Overall, limited research has been performed, mainly because very few missions were planned for *in situ* exploration. However, ESA has had several research & development activities related to landing small scientific payloads, including work on crushable structures and airbags for Marsnet and Intermarsnet, when a full-sized inflatable landing system was tested. The activity then moved to the national level; Beagle2 is being developed under private and institutional UK funding. However, it is now being addressed by an ESA Technology Research Programme in support of the BepiColombo mission to Mercury. An inflatable landing system for a crew-return capsule has also been developed under ESA contract, and tests of a scaled model were performed.

10.5 Justification and Rationale

Landing technology is obviously of paramount importance for any planetary exploration because it enables *in situ* exploration of the target body. Also, any progress made in structures and landing control systems would benefit the launch vehicle industry.

10.6 Technology Roadmap (Next 30 Years)

The first step, which could be achieved in the next 5 years, is the flight demonstration of European inflatable landing technology, building upon the solutions used by Beagle2 and the research & development activities of former TRP programmes. The activity could then be tailored to support the yet-to-be defined exploration missions

10.7 Technology Programme Proposal

2002-2005	**€5 million**
Further development of landing technology (materials, interfaces/joints, stability, structural efficiency) building on existing experience (Beagle2, MarsNetlanders) for better integration and efficiency	€1.5 million
Further development of inflatable landing technology for several classes of landers (materials, folding techniques...)	€1.5 million
Initial development of a landing-gear concept to be adapted to a Columbus-type structure	€1.0 million
Further development of a typical and integrated scientific package for planetary investigations	€1.0 million
2006-2007	**€10 million**
Development of an inflatable landing device	€2.5 million
Flight testing of the above device	€5.0 million
Development of a landing-gear concept	€2.5 million

11 Lightweight Ceramic Ablators (LCAs)

11.1 Introduction

Future exploration missions will require highly reliable and mass-effective planetary landing technologies. For planets with an atmosphere, a heatshield is needed to protect the probe from entry heating. The shield is generally the lander's heaviest component, considerably limiting the payload mass delivered to the surface. This implies an increase in the number of missions needed to bring the same hardware to the surface, with the consequent large increase in the cost and complexity of the programme. For sample return missions, the sample mass delivered to Earth is very sensitive to the dry mass of the planetary landing system. A reduction in the heatshield mass yields a large increase in the returned sample.

Technologies to reduce the mass of the thermal protection system mass are therefore beneficial at the system level in an exploration programme.

11.2 Technology Item Description

High mass-efficient ablative materials for heatshields, known as lightweight ceramic ablators, combine the good thermal resistance of ceramic materials with more conventional ablative resins, resulting in a very high specific heat of ablation at low density.

11.3 Status

Owing to their simplicity, reliability and low cost, ablative materials are still the preferred thermal protection concept for planetary entry. For entry at high velocity or in high-density atmospheres (Venus, Jupiter), the heat fluxes are so high that the only available protection is from high-density ablative materials (carbon-phenolic).

Many ablative heatshield materials are available in Europe. They were principally developed for Earth reentry (moderate heat fluxes) and Mars and Titan (Huygens) entry (low to medium fluxes). Ablative materials from this class are well advanced and mature and no further development is deemed necessary. However, in the high flux range, only the rather heavy carbon-phenolic material is available.

US progress in LCAs is reported in H.K. Tran, D.J. Rasky & L. Esfahani, 'Thermal Response and Ablation Characteristics of Lightweight Ceramics Ablators', *J. Spacecraft & Rockets*, **31**, No.6, 993-998, 1994.

11.4 European Technology Programmes

Ablative materials have been developed within ESA's MSTP and TRP programmes and within several national and military programmes.

11.5 Justification and Rationale

Preliminary computations show that lightweight ceramic materials can provide mass savings of up to 50 % compared with high-density ablators. Missions involving entries in high-density atmospheres or at high speeds (Venus, Jupiter, etc.) will benefit from this mass reduction.

11.6 Technology Roadmap

The technology roadmap remains to be determined.

11.7 Technology Programme Proposal

Investigation at material level (12 months)	€200 000
Manufacturing of samples and testing (6 months)	€300 000
Manufacturing of demonstrators (large heatshield sections) (12 months)	€300 000
Total Cost	**€800 000**

12 The Martian Atmospheric Environment

12.1 Introduction

Direct or indirect observations of the environmental conditions in the martian atmosphere are too sparse to compile a global spatial and temporal database of the conditions prevailing at a given location, at a given season or time of day. Such a database is nonetheless useful for the analysis of reentry or aerobraking, and the design of surface landers and remote sensing orbiter instruments. A database was constructed with the help of a general circulation model (GCM) of the martian atmosphere, originating from the merging of two GCMs previously developed separately at LMD (Laboratoire de Météorologie Dynamique, CNRS, Paris) and AOPP (Atmospheric, Oceanic

Table A4.2: Euromars Database Variables.

Variable	*Unit*	*2D or 3D variable*
Surface pressure	Pa	2D
Surface temperature	K	2D
CO ice	kg m^{-2}	2D
Surface emissivity	–	2D
Atmospheric temperature	K	3D
Zonal wind	m s^{-2}	3D
Meridional wind	m s^{-2}	3D
Density	kg m^{-3}	3D
Turbulent kinetic energy	m^{2} s^{-2}	3D

and Planetary Physics, Oxford, UK). Specialists from the Institute of Astrophysics of Andalusia, Granada, E, reinforced the team at a later stage. The ESA TRP (Martian Environment Models 11369/95/NL/JG) financed the work. TRP funding for this activity continues to the end of 2002.

12.2 Status of the Euromars Database

The database contains nine variables (Table A4.2) in a 3.75x3.75° horizontal grid for 32 altitude levels (5 m to 120 km) and different dust scenarios. Mean fields are stored 12 times per day and for 12 seasons to allow adequate resolution of the diurnal and annual cycles. Interpolation software is provided for easy interpolation at any location and time. A season is defined as a variation of 30° in solar longitude, which corresponds to a variable length of 50-70 days. Variability of dynamical variables at small and large scales can also be retrieved. The current database (version 3) extends to 120 km, but an extension to 250 km is under construction. The data generated by numerical simulations have been validated with the available observations (Mariner 9, Viking, Mars Pathfinder, Mars Global Surveyor).

The quality of this database continues to increase as new martian data are released. It is considered to be very reliable for altitudes up to 80 km, and is certainly the best thermal model of the upper atmosphere (up to 120 km). It is an essential tool for entry, aerocapture and aerobraking studies, but also for determining environmental constraints for rover, aeroplane, balloon and kite operations and the energetic potential of martian surface winds.

12.3 Distribution of the Database

The database can be accessed at *http://www.jussieu.fr/mars.html* or ordered from LMD or AOPP for intensive use. It has been installed at numerous centres. It is used by CNES in Toulouse for feasibility studies of aerocapture of their Mars sample return mission and for the preparation of the entry phase of the Netlander mission. It has also been installed at:

— the Geophysical Research Division of the Finnish Meteorological Institute, to assist the design of the surface module of the Netlander network;

- the Cosmic Physics Group of the Astronomical Observatory of Capodimonte, to prepare for the analysis of Planetary Fourier Spectrometer (Mars Express) data and of other martian observations;
- at the Rutherford Appleton Laboratory, UK, for the design of Beagle2's thermal protection.

12.4 Future of the European Martian Climate Database

The database will continue to improve with the progress of Martian science, provided funding is available at a level of about €150 000 per year after 2002.

12.5 Application to Other Solar System Bodies

Similar atmospheric models would be necessary to plan aero-gravity assist manoeuvres at Venus on the way to the outer planets and their satellites. Because of many features common between the atmospheres of Mars and Venus, some of the current developments for Mars (especially the modelling of the thermosphere) can be reused for Venus. To create a atmospheric database for the Venus troposphere would require a specific effort at an estimated cost of €600 000.

13 Synthesis: Technology Programme Proposal

The following funding profile (in €k) is proposed for the period 2002-2006:

#1: Aerothermodynamics of hypersonic entry vehicles
#2: Advanced heatshields
#3: High-speed entry demonstrator (Phase-A)
#4: High-speed entry demonstrator
#5: Aerocapture demonstration (Phase-A)
#6: Aerocapture demonstration
#7: Landing and lander technology
#8: Lightweight Ceramic Ablator
#9: The martian atmospheric environment

	FY02	*FY03*	*FY04*	*FY05*	*FY06*	*FY07*	*Total*
#1	200	200	200	200	200		1000
#2	200	400	400	400	400		1800
#3		200	200				400
#4				3000	15000	12000	30000
#5		200	200				400
#6				3000	15000	12000	30000
#7	300	400	1600	2700	3000	7000	15000
#8	200	450	150				800
#9		150	150	150	150		600
Total	*900*	*2000*	*2900*	*9450*	*33750*	*31000*	*80000*

Annex 5

Crew Aspects of Exploration

Annex 5 Contents

1 Introduction

Manned exploration of the Solar System means, essentially, exploration of the planetary and satellite bodies. It does not involve, for example, telescopic observations or other remote investigations. With the exception of the Moon, all these bodies pursue orbits around the Sun that are very different from that of Earth. In addition, and unlike robotic exploration, all journeys are expected to be 'round trips'. Given the constraints of current launchers and propulsion systems, manned exploration beyond the orbit of the Moon therefore implies long journey times with extended surface stays in locations that are very remote from Earth. The crew must be, to a very large extent, self-sufficient: life support consumables (oxygen, water, food) must be recycled, biohazards and chemical contamination must be controlled, and any medical emergencies must be handled on board with only limited assistance possible from Earth. The weightless and interplanetary radiation environments are also extremely constraining – possibly potential 'show-stoppers' for manned Solar System exploration. Without adequate counter-measures, a crew arriving on, for example, the martian surface after some 6 months in weightlessness will be in no condition to perform serious work or to respond to emergencies, particularly if these involve EVA. The radiation environment, in particular high-energy cosmic rays and solar flares, is also extremely dangerous and requires special attention, most importantly during interplanetary travel. In this context, EVA during travel through the Solar System should be limited to emergency situations and limited in duration. The suit itself must provide adequate radiation protection with consequent mass penalty. Measures must be taken during interplanetary and lunar transfers for special shielding in case of solar events and adequate shielding to maintain total exposure at reasonable levels. For planetary surface operations, assuming a degree of atmospheric shielding, radiation is less of a problem but mass becomes crucial. Also, the crew will be expected to operate regularly and for extended periods outside on the surface where there will be other dangers such as dust and sharp objects. Both safety and logistical considerations will dictate a maximum utilisation of *in situ* resources (see Annex 6).

Many of the above problems have already been tackled in the context of Europe's participation in the International Space Station (ISS) and its evolution. In addition, some technology developments have begun that have manned planetary exploration as their specific long-term goal. However, considerable work still needs to be done in all the above areas before a human crew can be sent to explore the Solar System. The scope, schedule and estimated cost of the work to be done are indicated in the following paragraphs.

Manned Solar System exploration will be a large undertaking and it is anticipated that Europe would not wish to undertake this alone. Several of our potential international partners – particularly the USA and Russia – have significantly more experience in manned space activities but, with the exception of the Apollo programme, this is limited to low Earth orbit. The technology also needs considerable advancement to support Solar System exploration. In many areas, Europe is competitive and in some it has a leading position. The establishment of appropriate participation by Europe in the crew aspects of international manned Solar System exploration missions will be an important task in the coming years. In this context, the International Working Group on Advanced Life Support (IALSWG), consisting of representatives of ESA, NASA, CSA and NASDA and co-chaired by ESA and NASA, can be of assistance.

2 Technology Item Descriptions

2.1 Regenerative Life Support Systems

In the context of manned Solar System exploration, the environmental control and life support system (ECLSS) consists of a number of discrete functions:

Environmental protection
— thermal control
— biological protection (microbial contamination monitoring and control)
— fire suppression

Air management
— air pressure control
— air composition control
— air revitalisation
— air quality monitoring and control

Water management
— water recovery
— water quality monitoring and control

Waste management
— collection and stabilisation of waste
— treatment to enable recycling

Food management
— food production
— storage

Many of these functions are amenable to conventional engineering techniques and, while important, do not involve critical technologies or procedures. The critical areas – the potential show-stoppers – from the ECLSS point of view come down to recycling techniques and biological hazard protection.

Consumable recycling can be accomplished by two fundamentally different approaches: physico-chemical techniques, which rely on classical engineering disciplines (filtration, absorption/adsorption, catalysis, electrolysis, distillation, etc.) and bioregenerative processes (transpiration, photosynthesis, bioconversion of waste products using microbial systems and plants, etc.). Each approach has its advantages and disadvantages. Physico-chemical systems are relatively easily understood, highly predictable and easy to control, and to date all manned space missions, including the ISS, have used exclusively physico-chemical life support systems. Disadvantages include a lack of flexibility to accommodate change, an inherent wear-out problem and the fact that no-one has so far discovered how to regenerate food from waste by purely physico-chemical means. Bioregenerative systems, on the other hand, are more complex to control but can recycle almost everything and possess a significant flexibility to adapt to changes.

The crew is not the only living entity in a manned space vehicle or habitat. Biohazards resulting from microbial action were a problem on the Mir space station and have, previously, resulted in the abandonment of earlier Russian spacecraft. The danger is to onboard equipment as well as to crew health and can be expected to increase in importance with complexity of habitats, length of mission and remoteness of mission (difficulty to instigate ground-based contingency actions). The mutation rate can also be expected to increase owing to the more intense radiation environment in interplanetary space. The problem is twofold, involving both detection and subsequent control.

2.2 Human Health Issues

Human health issues are conditioned by the time spent travelling and the duration and nature of activities at the destination. Different scenarios can be envisaged:

- LEO missions, typified by insignificant travel times and capability for almost immediate evacuation back to Earth;
- lunar missions where *in situ* treatment must be possible but return to Earth can be accomplished within a few days;
- planetary missions where intervention from Earth becomes very difficult and medical evacuation to Earth virtually impossible. Of these, planetary missions are, not surprisingly, the most challenging and will determine the technology developments required.

Human health issues need to address the basic functions below.

Prevention

This covers health maintenance and problems of deconditioning, and focuses primarily on cardiovascular, musculo-sensory and bone deconditioning. Prevention needs an adapted pharmacotherapy associated with devices such as lower body negative pressure (LBNP) facilities, muscle stimulators, ergometers and treadmills with elastic bungy cords. Current regimes for countering the effects of prolonged weightlessness include extensive periods of exercise on the part of the crew, a discipline that is not easy to maintain for relatively short periods in LEO and can be expected to be more problematic for long interplanetary trips. Other, more radical, countermeasures such as provision of artificial gravity need to be studied.

Diagnostic systems

Health screening and diagnosis will require sophisticated imaging systems based on ultrasound and devices for exploring cardio-vascular, cardio-pulmonary, musculo-sensory and bone systems. For planetary missions, in particular, they should be complemented by powerful imaging techniques such as whole-body-segment imaging using X-rays or magnetic resonance imaging (MRI). Blood and urine analysis and the more common microbial testing will also be required.

Treatment

Treatment, particularly for planetary missions, will be the most complex area. It will be severely limited in scope owing to volume and mass limitations and to the limited medical training of potential crewmembers. Any surgical procedures necessary during interplanetary flight will also (probably) need to be performed under weightless conditions. Resuscitation/ anesthesia units, patient conditioning units, surgical tools and logistics, fracture-control devices, cleaning/sterilisation, blood storage or blood replacement material will be necessary. Particular attention will need to be given to ensuring the long-term stability of potentially perishable parts and reagents. Minimally invasive tools and procedures will be favoured. Technology to treat tooth decay will need to be considered. Given the limited medical expertise on board, provision of refresher/training material will be an important issue.

2.3 Radiation Protection and Biological Effects

Radiation hazards are a strong limiting factor in manned exploration of space. Whereas crews in LEO are protected by the Earth’s magnetic field from much of the cosmic and solar particle-event environments and are orbiting low enough to experience low exposure to the trapped radiation belts, the situation is very different for manned missions beyond this. For example, had an Apollo mission been flying during the August 1972 solar proton event, the result would have been severe radiation sickness and possibly loss of the crew. Solar System exploration missions, characterised by long mission times involving many months of interplanetary travel, must expect to encounter such events, particularly during solar activity maximum periods, and must be designed to proceed without hazard during them. In this context, techniques for predicting and monitoring the occurrence of solar proton events, and predicting their propagation through the Solar System, are required to provide sufficient warning for interplanetary crews to take appropriate action. Special attention to radiation shielding in all mission phases and scenarios needs to be analysed, including cruise, EVA, surface operation and surface accommodation. Extensive personal and vehicle/ habitat radiation environment monitoring will be required.

2.4 EVA Issues

As alluded to in the Introduction, there are two distinct scenarios that need to be considered for EVA: interplanetary travel and surface operations.

EVA during interplanetary travel

Arguably the biggest hazard will be from the interplanetary radiation environment. Space suits that can provide adequate shielding will be relatively massive. On the other hand, major construction tasks, of the sort encountered in the context of the ISS, are not expected. EVA during interplanetary flight will likely be for emergency situations, implying limited EVA time and a limited number of EVA suits. It is not clear that a heavy, autonomous space suit is the optimum approach in these circumstances. It needs to be studied to what extent, given the expected brief exposure times, a lighter system, perhaps using umbilical connections to exchange consumables and data with the spacecraft, might be the better way forward.

EVA during surface operations
Unlike the above scenario, surface EVAs will be routine and relatively frequent, and will be an integral part of the exploration process. Important differences between space and the surface include gravity, dust, sharp/abrasive objects and possibly some sort of atmosphere. On the other hand, the radiation danger should be reduced by the presence of the planet on one side and possibly atmospheric shielding on the other. For destinations with thin or non-existent atmospheres, well-shielded surface habitats and EVA radiation hazard warning systems are nevertheless required. Suit materials must be tough and joints resistant to dust penetration. Suits must be easily cleaned to prevent uncontrolled transfer of material from the surface into habitable volumes. The most serious problem, however, may well concern weight. The Shuttle suit has a mass of about 112 kg, of which 73 kg is for the backpack life support system. On the surface of Mars, this translates into an unacceptable 40 kg. In addition, although thin, the martian atmosphere is dense enough to preclude the use of a conventional sublimator for thermal control (even supposing that the associated loss of water were acceptable). It is hence necessary to distinguish between visits to small bodies with little atmosphere (Moon, asteroids) and missions to larger planetary bodies typified, by Mars. In the latter case, the approach of a fully autonomous system such as the Shuttle, ISS or Apollo designs may be acceptable. For planetary surfaces such as Mars, weight constraints may – will probably – dictate a different approach. Options include umbilical connections to rovers or equipping suits with limited amounts of life support consumables that can be replenished from a nearby rover.

3 Status

3.1 Regenerative Life Support Systems

Europe began to develop ECLS technology across a broad front in the mid-1980s, in support of the ambitious manned programme foreseen at that time (Columbus Attached Pressurised Module, Man-Tended Free-Flyer, Hermes and EVA Suit 2000). Since that time, and in response to the significant evolution in Europe's manned space ambitions, efforts have focused on a few important key areas:

Air revitalisation: technology has been developed to the level of a 3-5 man equivalent air revitalisation system demonstrator which extracts carbon dioxide from the air and, with the aid of a Sabatier catalytic reactor and electrolyser unit, recovers the oxygen for the crew. This equipment is significantly superior to the air revitalisation system baselined for the ISS and is being actively considered for ISS upgrade. Associated accommodation studies are in progress and flight testing of the gravity-sensitive electrolyser is in preparation. The system has been tested for use in submarines (Germany) and its carbon dioxide absorption subsystem considered by the Airbus Company for future passenger aircraft. Prime contractor is Astrium-FHN (D) with subcontractor EFPL (CH). Precursor studies involved ORS (A).

Air composition monitoring and control: carbon dioxide and oxygen sensors, based on infrared spectrometry and paramagnetic techniques respectively, are available from Draegerwerke (D) and are included in the Columbus module. The same company has developed catalytic oxidation techniques for the removal of organic contaminants from the atmosphere, techniques that have considerable synergy with applications in the automotive industry. In addition, biological techniques have been studied (SPE, NL; BioClear, NL) aimed at using bacterial cultures, constrained within membrane systems, to digest atmospheric trace contaminants (biological air filter, BAF).

Air contaminant monitoring: trace-contaminant monitoring equipment, based on a Fourier-transform Infrared (FTIR) Spectrometer and capable of measurements in the ppm range, has been developed to the level of advanced breadboard. It has demonstrated an excellent performance when compared with other technologies and equipment in blind sample tests sponsored by NASA, and it is under active consideration for ISS enhancement. Flight demonstration tests are planned. Potential terrestrial applications include submarines, aircraft and large building complexes (offices, hospitals). The industrial team currently includes Astrium-FHN (D), Kayser-Threde (D) and Sintef (N).

Water recycling: membrane-based techniques have been developed to recover potable water from ‘grey’ water (e.g. shower water). The technology has been developed by TechnoMembranes (F) and is at the level of advanced breadboard. Automatic operation covering several months has been demonstrated and the technology has been adopted by a well-known European producer of mineral water.

Bioregenerative life support: Europe has, since 1989, been developing the technologies necessary to establish, maintain and control closed ecosystems, via the MELISSA project. MELISSA is a joint venture partnership consisting of eight partners in five countries (B, CND, E, F, NL). The current status is that a ground demonstration of a closed-loop of five sequential bioreactors, together with a higher-plants compartment, is at an advanced stage of development. Flight testing to assess the effects of space conditions (hypogravity, radiation, etc.) on the MELISSA (bio)components is in preparation. Terrestrial spin-off has included two patents. Technology developed for the nitrifying compartment of MELISSA has been adopted by the wastewater industries in Denmark, France, Germany, Italy, Switzerland, Turkey and the UK. A biomass sensor developed for MELISSA has been adapted and is in continual use for production of Cava by Freixenet (E).

Microbial contamination monitoring: developments have recently started with bioMérieux (F) to adapt DNA finger-printing techniques for the (semi-)automatic monitoring of the microbial status in closed cabins. Although of great importance for manned spacecraft, the technology has strong potential for terrestrial applications, such as in the food production industry and hospitals.

Physico-chemical atmosphere management and air revitalisation technology is also available elsewhere and, in particular, in the USA, Russia and Japan. European equipment is, however, competitive. European trace gas monitoring techniques, based on the FTIR principle, appear to be ahead of the field, particularly in the area of processing of the data (more robust and greater accuracy). Bioregenerative life support has been studied extensively in the USA and Russia and, more recently, in Japan. The focus on understanding and controlling a complete ecosystem, with the aid of a simplified, deterministic microbial system (MELISSA) has given Europe an internationally acknowledged lead in this area that should be exploited. Finally, it should be noted that the work already performed with a view to space applications has placed Europe in an excellent position to respond to the increasing concerns regarding the terrestrial environment.

3.2 Human Health Issues

Several ergometers and treadmills have been tested and used during Mir and Shuttle missions. Results have indicated that, although the approach was effective, it was not efficient and the crew had the impression of working long and hard for little return. In this context, ESA is collaborating with Prof. Tech and Dr. Berg of the Karolinska Institute (S) in the development of a promising novel approach to exercising using the resistive exercise concept of the Flywheel. On the subject of bone demineralisation, research has been undertaken in Europe by Prof. Goodship (UK) to develop a device that attempts to simulate the mechanical shocks to the heel bone associated with walking in a 1 *g* environment. Promising results were obtained during experiments on Mir. Europe also has experience with LBNP techniques and has undertaken preliminary research with adapted pharmaco-therapy, such as non-steroidal anti-inflammatory drugs.

Small 'cold' (i.e. non-radioactive) diagnostic tools for the cardio-vascular system have been successfully used in space by Europe, Russia and the USA. Bone diagnostic devices, immuno-biochemistry analysis systems, microscopes and X-ray tubes are under development or have been developed, sponsored by TRP and GSTP. New principles for low-energy X-ray collimators have been successfully tested. Body-segment imaging systems (X-ray and MRI) exist on the ground but will need considerable adaptation for flight.

The subject of treatment has received little attention to date, since the requirements are not severe for current LEO manned missions. The technology is used daily on Earth but will need adaptation and further development for space use.

3.3 Radiation Protection and Biological Effects

Europe is at the forefront in the world concerning radiation interactions, in large part due to the CERN-originated Geant4 software used for analysing the effect of shielding. ESA is the only space-agency member of the Geant4 Collaboration and, as such, has a prominent position in space radiation-related developments. ESA has a vigorous programme to develop radiation monitors, currently limited to monitors for unmanned missions. They are planned to fly on several spacecraft (Rosetta, Herschel, Integral, Galileosat) and will constitute important elements in a projected network to support space weather predictions. On the subject of the effects of radiation on humans, both the US and European radiobiological communities are conducting basic research into the effects of radiation at the cellular and DNA levels. There is also an ESA-sponsored and Geant4-based activity to attempt a rigorous approach in eventual computer simulations of these highly complex effects.

3.4 EVA Issues

Technology development was undertaken in Europe in support of European space suit studies, culminating in the EVA Suit 2000 studies in the early 1990s. Expertise existed, at that time, in the areas of high-strength, abrasion-resistant outer fabrics (Astrium-Bremen, D), carbon dioxide partial pressure sensors (Draegerwerke, D) and low-power fan/pump/separator (Technofan, F). Since the discontinuation of EVA Suit 2000 development in 1994 little, if any, EVA-related work has been done in Europe and, as a result, the above expertise must be considered somewhat ‘rusty’. Most of the expertise resides in the USA and Russia, as a result of their long legacy of manned space flights. Nevertheless, planetary exploration raises several new problems, as indicated above, and European experience, particularly in the area of the outer suit fabric, could provide a valuable contribution.

4 European Technology Programmes

4.1 Regenerative Life Support Systems

Development of (physico-chemical) air management technology and, in particular, air revitalisation technology has, since 1985, been sponsored by several ESA budgets, including the Columbus preparatory programme, Hermes preparatory programme, TRP, GSTP and technology transfer programme, and has been closely harmonised throughout with German national technology activities. It has also benefited from significant company investment, both as part of development and to support recent and current efforts to exploit the results in an ISS context. Consistent with the relative maturity of the air revitalisation technology, funding is currently predominantly from GSTP, national and company sources. Physico-chemical water recycling technology has been developed since 1988 using funds from both the TRP and terrestrial transfer sources.

Developments in bioregenerative life support started in 1988, reflecting the anticipated long lead-time for such novel technology. Funding levels were low, however, owing to the lack of an identified long-term plan for human space exploration. Funding sources included the TRP, technology transfer programme and company investments mainly in the context of the MELISSA joint venture partnership. More recently, as interest in human space activities after ISS has increased, other funding sources have come into play, in particular the GSTP, EMIR and national programmes. Basic research leading to a ground demonstration of the MELISSA loop continues to be financed on an approximately 50/50 basis by the Agency and its partners, under the terms of the joint venture. One exception is the very significant contribution from Canada towards the creation of sealed plant growth facilities to enable plant performance to be measured under different atmospheric pressure and composition. The important area of flight testing, now rapidly increasing in importance, is mainly the province of the GSTP and EMIR programmes. Efforts to use the research results to support development of real life support systems have only recently started and are currently funded exclusively by the GSTP. Microbial contamination monitoring studies have also started only recently. They are initially covered by the GSP and GSTP programmes but are expected to benefit from considerable company co-funding in due time, reflecting the strong potential for terrestrial commercial applications.

4.2 Human Health Issues

Work on the Flywheel is currently funded through ESA's Microgravity Applications Programme (MAP). Prof. Goodship's bone demineralisation device was funded mainly by his own laboratory, complemented with an Agency contribution in the area of adaptation for space application. Work on the LBNP device was funded by DLR. Cardio-vascular and bone diagnostics are rather well mastered in Europe, through the scientific instruments developed and used in several spaceflights, funded by both ESA and national agencies (DLR, CNES), or under development within the TRP and GSTP programmes. Development of a compact device for measuring lung function is currently under development with ESA funding.

4.3 Radiation Protection and Biological Effects

In the late 1980s ESA undertook the 'PARIS' study of radiation effects on astronauts. In the frame of the Geant4 collaboration, ESA-originated developments have generated a significant medical user community both in Europe and in the USA. This can provide significant feedback spin-off benefits for manned space exploration. Developments also include GSP-funded space weather studies, development of simulation tools within the TRP and development of radiation monitors within the GSTP, GSP and the general budget. National agencies also have expertise in radiation effects, with a focus on the Columbus programme, and in radiation monitor developments.

4.4 EVA Issues

Technology developments related to the EVA studies undertaken in Europe during the 1980s and early 1990s were financed mainly by the Hermes preparatory programme and by the TRP. At the present time, no activities are included in Europe's technology programmes on the subject of EVA.

5 Justification and Rationale

5.1 Regenerative Life Support Systems

An adult human consumes, on average, about 0.85 kg of oxygen per day and generates about 1 kg of carbon dioxide. The carbon dioxide must be removed from the air (concentrations above about 4% rapidly become toxic) and the oxygen replaced. Each crewmember also requires about 4 kg of potable water for drinking and food preparation, together with 10-20 kg for hygiene purposes. To this must be added some 0.6 kg per day for solid food. Hence, without any recycling of consumables, each crewmember requires about 15.5-25.5 kg to be resupplied every day! The wide range associated with the hygiene water requirement is dependent mainly on the techniques adopted for clothes and cooking/eating-utensil hygiene (washing machines and dishwashers are heavy consumers of water). On the above basis, the 7-man crew of the ISS will need to be resupplied with 9.8-16 t every 90 days, and a 6-man Mars crew would need to take, for a 880-day mission, 82-135 t of life support consumables along with them.

For exploration of near-Earth space, the financial penalty of such an approach is arguably the only problem. However, for missions beyond the Moon and, in particular, to other planets such as Mars, another problem arises that concerns the security of the resupply system and flexibility to adapt to unexpected events (missed return launch window, for example).

Human space exploration hence requires a degree of recycling of consumables for a combination of economic, logistical and safety reasons. The degree of recycling increases with the distance from Earth and the length of mission.

In LEO, economic arguments require recycling of water and recommend recycling of oxygen. Recycling of solid waste and on-orbit production of food is not worthwhile. For lunar missions to, for example, a man-tended facility, air and water recycling would be required for mainly economic and safety reasons. Food production would be necessary only when a permanently manned facility is contemplated. For missions to the planets, where transit times of many months and on-surface stay times of years must be contemplated, comprehensive recycling and regeneration of consumables will be necessary.

5.2 Human Health Issues

Manned space travel is still a risky enterprise. When immediate travel back to Earth is not possible, measures must be taken to allow performance of those procedures necessary to preserve crew health. Surgical procedures should be limited to life-threatening conditions or emergencies and priority must be given to prevention. Where surgery is unavoidable, only minimally invasive surgery should be considered. Whatever tools or procedures are developed, they should be adapted to the specific mission, be as simple as possible and rely on minimal logistics. Development should be performed in close collaboration with the health-care industry, for knowhow and cost reasons. This will reduce development costs and, by introducing new requirements and bringing new teams together, will stimulate new product development and increase European competitiveness.

5.3 Radiation Protection and Biological Effects

Space radiation is a potential show-stopper for manned interplanetary exploration. Its effects on humans are also not well understood. Most information of this nature is based on the results of the use of atomic weapons during World War II and nuclear accidents since. Such information is of limited usefulness owing to the substantial differences between nuclear and space radiation characteristics (type of particles, energy spectra, etc.). Tests on human subjects are understandably difficult, in view of the risks of long-term genetic and other cell damage. In view of its criticality for human spaceflight, the subject is under active study in several parts of the world, most particularly in Europe and the USA. The full protection of an interplanetary spacecraft against possible solar proton events would result in prohibitive mass and therefore cost penalties. It is important to develop a strategy, involving, for example, prediction, monitoring and use of storm shelters to reduce the risks to acceptable levels. Modelling the interaction of space radiation with a spacecraft is complex and, in this area, Europe has a commanding position that should be preserved and built upon. The understanding and prediction of space weather will be crucial for safe interplanetary travel and the efforts already in progress concerning modelling and monitoring need to be continued and enhanced.

5.4 EVA Issues

Although the technology for EVA in LEO and on the surface of the Moon has been mastered – although admittedly not in Europe – this technology will be inadequate for the serious task of exploring the surface of planets with significant gravity and rugged, dusty environments. In this sense, EVA technology must be considered an enabling technology for manned Solar System exploration. In this context, Europe's most valuable contribution could be in the area of the surface suit, since the in-space suits are the entrenched domain of our American and Russian colleagues. This will make maximum use of past European developments associated with EVA Suit 2000 and particularly the development of the external fabric. Terrestrial spin-off has included protection for fire fighters and application to military/police bullet-proof flak jackets.

Studies will need to be performed to identify, for candidate operational scenarios, the constraints and driving requirements for planetary surface mobility suits and to translate these into requirements for technology developments. It may be confidently predicted that the areas requiring development or further improvement will include suit materials such as footware, gloves, thermal control systems and life support.

6 Technology Roadmap

Assuming a technology need-date of about 2015, the overall roadmap for crew aspects of exploration is as shown in Fig. A5.1. In the interests of clarity and to reflect the main development priorities, the subject of 'regenerative life support systems' is divided into 'regenerative life support for interplanetary travel', 'bioregenerative life support for surface habitation', 'cabin environment quality/contamination monitoring' and 'ECLS system-level testing/demonstration (on-ground)'. It should be emphasised that, particularly in the areas of regenerative life support for interplanetary travel and cabin environment quality/contamination monitoring, considerable synergy exists between the needs of the Solar System exploration programme and evolution of the ISS. In almost all areas of development for manned Solar System exploration, the ISS constitutes an essential facility, both for the generation of research data and as a technology testbed.

As intimated in the Introduction, there is considerable scope for collaboration with international partners. For example, while it is essential to perform long-duration tests of advanced life support equipment under realistic conditions (i.e. in a closed, manned environment), such facilities are expensive and consideration should be given to making use of existing facilities such as the NASA Johnson Space Center BioPlex complex. Likewise, the establishment of a space weather monitoring network need not be the sole responsibility of Europe, and advantage should be taken of all opportunities to hitch a ride for radiation monitors on spacecraft destined for interplanetary space. Health issues are also very complex and should be addressed at the international level. Many teams throughout the world are working on these issues. In many instances, this apparent duplication is justifiable in view of both the highly competitive spin-off potential and the diversity of potential solutions for a given problem. However, it is recommended that, at an early stage, an international working group should be established to keep developments under review and to provide advice to sponsoring agencies concerning unnecessary duplication or areas with insufficient coverage.

7 Technology Programme Proposal

Although Europe is by no means starting from 'ground zero', it is still not possible, neither would it be credible, to attempt yet the definition of a detailed technology programme covering the next 15-20 years. Accordingly, the proposal that follows is limited to those activities that need to be started during the period up to 2006.

Fig. A5.1: Crew Aspects of Exploration – Technology Development Roadmap.

	2000	2005	2010	2015	2020	Cost Est. M€
Regenerative life support for interplanetary travel						
Testing/exploitation current systems on ISS						5.0 *
Studies for next generation systems						1.0
Technology development						6.0
Flight verification						5.0 *
Bioregenerative life support for surface habitation						
Basic R&D and on-ground demonstration						10.0
In-space testing using ISS						7.0 *
Engineering development						15.0
Cabin environment quality/contamination monitoring						
Air quality monitoring						1.0
Microbial contamination monitoring						15.0
ECLS system-level testing/demonstration (on-ground)						
Development of man-rated simulator						10.0
"Closed door" test campaigns						10.0
Human health issues						
Human health in-flight and on-surface strategies						1.2
Technology developments						10.0
Flight validation						6.0 *
Radiation protection and biological effects						
Develop/optimise radiation monitoring equipment						3.0
Establish "space weather" monitoring network						1.0
Establish/validate "space weather" predictions						1.5
Upgrade radiation shielding modelling tools						0.8
Effects on crew and operations strategy						0.5
EVA issues						
Strategies for in-flight and on-surface EVA						0.9
Development of critical technologies						4.0
Development of system demonstrators						10.0
Tests using ISS						15.0 *
					Total:	138.9

*Notes: 1) Costs marked with a symbol * do not include the costs for flights*

2) Costs are ROM estimates and include contributions from technology programmes (TRP, GSTP) and ISS-related D/MSM programmes

The near-term priorities in regenerative life support are basically to build on the developments that are already in progress while exploring possible next-generation techniques promising greater reliability and power/mass-efficiency. The current efforts in air and water recycling should be continued and enhanced to permit a higher degree of loop closure than is acceptable for the ISS. The MELISSA bioregenerative life support programme needs to be accelerated to move more rapidly from the current stage of ground-based research to embrace comprehensive space testing. The results of these and ground-based research must then be exploited to develop and validate the technology for the engineering of closed and controllable ecosystems that can support, more-or-less indefinitely, the life of a crew during interplanetary missions. In addition, the current programmes to develop monitoring equipment to measure both chemical and microbial contamination in the human environment need to be continued. Ultimately, it will be necessary to perform extended, ground-based, testing of the complete closed-loop life support system using a human crew. No facilities yet exist in Europe to support such tests but they are in the process of being established in the USA (BioPlex). Possibilities for collaboration in this area should be explored in due time.

On the subject of human health issues, in parallel with the on-going hardware developments concerning the immuno-biochemical analyser and bone-scanning device (funded by the TRP/GSTP), strategies need to be established for countering in-flight deconditioning, the performance of health screening and diagnosis, and medical treatment. Following this, the necessary technology developments can be identified, prioritised and breadboarding initiated. It may be anticipated that important priorities will include body segment imaging and bone quality monitoring. On the subject of treatment, it will be necessary to refine the technological needs for minimally invasive surgery before initiating specific developments. An international working group on human health in space should be established to minimise unnecessary duplication and advise (inter)government agencies or other sponsoring bodies concerning technology development needs.

In the critical area of radiation hazards for manned interplanetary missions, major priorities are to understand and be able to predict the environment and to establish the tools necessary to design adequate shielding. In this context, development of low-mass, long-life radiation monitors needs to be continued. In addition, the establishment of an international monitoring network to permanently monitor the interplanetary radiation environment, by including radiation monitors whenever possible on interplanetary spacecraft, should be accelerated and supported. The sensitive issue of the effects of prolonged exposure of the crew to space radiation also needs to be tackled.

On the subject of EVA, it is likely that the techniques adopted for LEO operations will prove unworkable either for interplanetary travel or for planetary surface operations, for reasons mainly of mass, environmental hazards and (at least for Mars) the existence of an atmosphere. Before major

Fig. A5.2: Priority Technology Activities, 2001-2005.

	2002	2003	2004	2005	2006	Current or proposed funding source
Regenerative life support for interplanetary travel						
Electrolyser flight test						Nat, Ind.
Methane pyrolysis technology demonstrator						GSTP
Integration of pyrolysis TD into air revitalisation system		250	250			Exploration Programme
Advanced air revitalisation technologies - study & predev.			400	600	750	Exploration Programme
Optimisation of core water recycling system technology	150	250	300			Exploration Programme
Heavily-contaminated water recovery - study & predev.			200		1000	Exploration Programme
Bioregenerative life support for surface habitation						
MELISSA basic R&D and on-ground demonstration						TRP, GSTP, Nat, Ind.
Microbial water treatment						GSTP
MELISSA-related flight tests - BIORAT						EMIR, GSTP
Others		400	550	750	950	Exploration Programme
MELISSA adaptation for space - Phase 1						GSTP
MELISSA adaptation for space - critical technologies			600	750	1600	Exploration Programme
Cabin environment quality/contamination monitoring						
FTIR trace gas monitor - flight demonstrator						GSTP, NASA
Trace gas monitoring system, design optimisation		200		600	1000	Exploration Programme
Microbial contamination monitoring for ISS						GSTP, TRP, Ind, ISS utilisation
Human health issues						
Strategies: counter-measures & diagnostics		150	200			Exploration Programme, GSP?
Strategies: medical treatment			250			Exploration Programme, GSP?
Technology development: diagnostics				300	600	TRP, GSTP, Exploration prog.
Technology development: counter-measures				300	700	Exploration Programme
Establish & support interplanetary crew health WG		50	5	5	5	Exploration Programme, GSP?
Radiation protection and biological effects						
Development of radiation monitors			350	350	350	GSP, GSTP, Exploration prog.
Modelling of the interplanetary radiation environment		400				GSP, Exploration Programme
Establish & support interplanetary rad. monit. network			150	150	200	Exploration Programme
Shielding prediction tools	50	100	150	150	200	TRP, Exploration programme
Radiation hazard assessment and effects on crew			100	150	250	Exploration Programme
EVA issues						
Assessment of in-flight & on-surface EVA strategies			400			Exploration Programme, GSP?
Identify critical technologies & establish requirements				200	200	Exploration Programme, TRP?
Totals (k€):	**200**	**1800**	**3905**	**4305**	**7805**	

developments in EVA can be contemplated, it is first necessary to assess the optimum strategies to be adopted for the in-flight and on-ground operations, and to identify and establish requirements for the associated critical technologies. It will also be necessary, in parallel with these activities, to define an appropriate European role in this area, given the relatively immature status of EVA technology in Europe when compared with our international partners in the USA and Russia.

Priority activities to be initiated in the period 2002-2006 are indicated in Fig. A5.2. Related activities that are already funded by, or planned under, other programmes are also indicated to illustrate the overall consistency and continuity.

Annex 6

In Situ Resource Utilisation

Annex 6 Contents

1 Introduction

In Situ Resources Utilisation (ISRU) means 'living off the land'. In our urge to explore the Solar System and to visit those celestial bodies that are within reach (Mars, Moon, Europa, asteroids), any product from indigenous materials that significantly reduces mass, cost and risk should be considered. The high upload mass requirements and today's launch capability (e.g. Ariane-5) means that ISRU is a prerequisite for missions beyond the Moon.

ISRU comes into play for producing propellants, reactants for fuel cells, and oxygen and water for life support. To ensure a safe return to Earth, the crew must be independent of risky supplies from Earth – the return vehicle must be ready waiting fully fuelled and provisioned.

ISRU covers a wide spectrum of products, ranging from consumables directly needed in support of the mission in the short-term to products of possible economical significance in the long-term. Metals or construction materials may be processed, which are useful for building the habitat, developing the surrounding infrastructure (e.g. roads) and providing radiation protection. Characterisation of the indigenous materials, however, is a prerequisite for designing the production processes.

Robotic missions may basically go anywhere. However, the most probable candidates for human exploration are Mars, the Moon and perhaps the jovian moon Europa, taking into account the travelling time from Earth and the relatively benign environments (although radiation will be a particular issue for Europa).

The lunar regolith was well characterised by Apollo, but much of the information is missing for Mars and Europa. Based on the available information, a process to produce oxygen on the Moon would look completely different from an oxygen process on Mars or Europa. Without a lunar atmosphere, oxygen has to be produced from oxygen-rich minerals. More than 20, mostly non-terrestrial, physico-chemical processes have been identified to produce oxygen from the solid lunar regolith, all requiring the build-up of an extensive chemical factory.

Mars has a low-density, almost pure carbon dioxide atmosphere, contaminated with nitrogen, argon, oxygen and some traces of water. The carbon dioxide would provide a readily accessible resource for oxygen production, while the nitrogen could be used for cabin atmosphere make-up gas. Well-established terrestrial processes like the Sabatier reaction or high-temperature electrolysis may be of use here.

Europa appears to have water ice, which may well be suitable for oxygen and hydrogen production, provided that sufficient power is available.

Initially, ISRU should focus on indigenous products that result in the maximum mass saving. Consequently, the highest priority should be on indigenous propellant production for rocket propulsion and life support consumables. Reactants for fuel cells may be considered as byproducts.

So far, water has not been confirmed on Mars or the Moon. Hydrogen, as an important element of water or reactant in the Sabatier process, if not indigenously available, inevitably has to be recycled and (re)supplied from Earth. If cryogenic hydrogen is carried, the extremely long mission duration imposes special constraints in order to minimise the hydrogen boil-off.

2 Technology Item Description

In the short-term, the most important objectives for ISRU are to generate indigenous propellants (methane, oxygen and carbon monoxide) and life support consumables (water, air) for the crew. The basic technology is the same for both. The ratio of the products is different or taken at a different stage of the process. This translates into different sizing for the production plants or different configurations.

The basic elements for life support consumables are water, oxygen and nitrogen. The preferred propellants are cryogenic oxygen and cryogenic methane in the ratio 3.5:1. The ratio is essential for ISRU on Mars to have the stochiometric product-ratio of oxygen and methane meeting that of the rocket engines.

There are several parameters that determine how the wanted end product may be obtained: the available base materials and the local environmental conditions with respect to provision of energy, cooling, dust, day-night cycle, gravity etc. To achieve a certain product, a series of steps have to be followed in the process:

Step 1: surface mining or material collection
Step 2: pre-processing
Step 3: production process
Step 4: liquefaction
Step 5: storage

Applying this scheme to oxygen production on the Moon means:

Step 1: collection of most oxygen-bearing minerals (silicate or oxides) by mechanical means e.g. an autonomous lunar rover in a highly dusty environment.
Step 2: separation and enrichment of the mineral feed (e.g. magnetically).
Step 3: raw material processing (more than 20 processes possible) varying from reagentless (e.g. pyrolysis) to reagents brought from Earth (e.g. oxygen extraction with fluorine). The selection of the process has to be based on product yield, simplicity, power requirement, byproducts, etc. Oxygen production is a power-intensive process. A preliminary estimate

of an oxygen process plant based on pyrolysis resulted in 90 kW/tonne for a year if the plant were operated only during the lunar day. Taking maximum advantage of solar energy during the lunar day, when the regolith is directly heated, the power may be reduced by 25-30%. The produced oxygen is available for propulsion and life support.

Step 4: liquefaction (more than six processes). Cryogenic oxygen is preferred for propulsion purposes. The lunar night can be an advantage by reducing the power requirements.

Step 5: special storage tanks (dewars) if the final product cannot be used immediately.

The production plant has to be autonomous in order to serve robotic missions as well as human missions.

To generate propellant on the Moon, methane (or hydrogen) would be brought from Earth in the short-term. In the long-term, hydrogen may be produced by heating the regolith.

The fact that Mars has a very low-pressure (~7 mbar) 95% carbon dioxide-rich atmosphere, mixed with 2.7% nitrogen, 1.6% argon and 0.13% oxygen, means the technology is simpler for generating propellants and life support consumables than on the Moon. Extensive use can be made of well-known terrestrial technology or physico-chemical technology specifically developed for life support. Applying the production scheme described above means:

Step 1/2: martian atmosphere collection, filtering and compression. After filtering, the carbon dioxide and nitrogen are separated. The carbon dioxide is pressurised to (typically) 1 bar or higher for further processing. The nitrogen is liquefied and stored according to steps 4 & 5 for use as the make-up gas in the crewed habitat's atmosphere. If the argon contamination is unacceptable for medical reasons, nitrogen has to be purified by selective molecular sieves or membrane filters. The separation of carbon dioxide and nitrogen is accomplished by using solid amine to absorb the carbon dioxide. The temperature variation during the martian day-night cycle may be sufficient to provide the energy for the absorption-desorbtion process. A compressor is needed for pressurisation.

Step 3: carbon dioxide is further processed through reduction with hydrogen (Sabatier reaction), producing water and methane. Methane is the preferred product for propellant. Water electrolysis regenerates the hydrogen, originally brought from Earth, and provides the oxygen. The Sabatier process produces oxygen and methane in the ratio 2:1. For high-efficiency propulsion, 3.5:1 is required. To produce the missing oxygen (also for life support), different technology is proposed: electrolytic reduction of carbon dioxide (high-temperature electrolysis), reverse water-gas shift and photocatalytic decomposition. The carbon dioxide from the martian atmosphere is used directly as feed stock. An alternative is to produce an excess of hydrogen and pyrolyse this to recycle the hydrogen. However, the residual carbon needs proper handling.

Step 4/5: liquefaction and cryogenic storage of all gaseous end products (methane, oxygen, carbon monoxide and nitrogen) would be required. Liquefaction requires large heat-lift refrigeration systems.

The production plants must be fully autonomous. For a safe stay on Mars and return to Earth, propellant and life support consumables must be generated before the crew leaves Earth. The return vehicle has to be confirmed as fully fuelled and provisioned with life support consumables. The boil-off rates of the cryogenic methane and cryogenic oxygen have to be controlled or compensated for to minimise loss.

Hydrogen upload is an issue in itself. The hydrogen may have to be transported and held in a sub-cooled cryogenic condition (e.g. 15K). Alternatives are being studied to retain the hydrogen cryogenically using cryocoolers to minimise boil-off during the Mars transfer. Uploading water as a hydrogen source is not an attractive option because oxygen is chemically abundant on Mars and is the heavier element.

System analyses and in-depth trade-offs are required to identify the most suitable technology for the processes, taking into account all parameters like the required process energy, fuel requirements, life support requirements, and the suitability of the process for local conditions.

3 Status

3.1 ISRU in Europe

3.1.1 Moon

European activities towards ISRU on the Moon have been rather limited. In Germany, DLR has studied a process to produce oxygen from the lunar regolith using fluorine as reagent. In 1994, ESTEC contracted AEA Technologies (UK) within the TRP to review the oxygen production processes as part of Lunar European Demonstration Approach (LEDA) programme. The work included the preliminary design of a flight experiment and a development plan of a 10 t production unit.

3.1.2 Mars

European activities towards ISRU on Mars are rather limited. However, taking into account the synergy with other disciplines such as life support, a scale of technology becomes available that is readily adaptable for its alternative use. As the carbon dioxide from the martian atmosphere is the base material for further processing, there is significant synergy with the Astrium FHN-developed technology for life support, specifically for air revitalisation based on the carbon dioxide removal-Sabatier reactor-water electrolyser-methane pyrolysis system as described in Section 3.1 of Annex 5. Considering that the carbon dioxide partial pressure in the crewed space atmosphere and the partial pressure on Mars are of the same order, it may well be that the Astrium-developed carbon dioxide absorber is adaptable for Mars.

The zirconium oxide-based high-temperature electrolysis technique, which appears to be very attractive for processing the martian atmosphere, is available from the (terrestrial) nuclear power industry. The technology was developed specifically to make economical use of waste high-temperature water steam by dissociating it into oxygen and hydrogen; it may also be used for carbon dioxide. However, zirconium oxide ceramic is very brittle and much research will have to be made to adapt it for space application. For this technology, significant synergy is expected with the life support application and the developments in fuel cell technology. Other technologies such as the 'Reversed Water Gas Shift' (RWGS), a well-known process in industry (steam reformation of methane), and photocatalytic carbon dioxide decomposition, in an early stage of development, have also been studied.

Liquefying technology (Stirling coolers, pulse-tube coolers, etc) exists for terrestrial applications but would need adapting for space application. High-lift cryogenic coolers to handle large amounts of gas would have to be developed (cooling power: 4W @ 20K for oxygen, and 15W @ 80K for methane). Storage technologies are a well-known terrestrial technology, which would require adaptation for the new environment.

3.2 ISRU in the USA

In the 1980s the major thrust on developing ISRU processes was aimed at oxygen production on the Moon, while in the 1990s the emphasis shifted to ISRU on Mars.

3.2.1 Moon

The lunar samples returned by Apollo provided a wealth of information on the chemical composition of the different minerals. More than 60% of the atoms are oxygen, but all of them are tightly bound chemically to other elements. The material characterisation allowed identification of those locations on the Moon for optimum oxygen production. The research focused specifically on the oxygen recovery process, identifying more than 20. Most were tested at laboratory scale using synthetic lunar minerals as the base material. However, the lack of a follow-up lunar exploration programme to drive the development meant that none of the technologies actually matured. The state of development has remained more or less at the laboratory level.

3.2.2 Mars

The interest in Mars increased significantly with the Mars Pathfinder project of 1996-97. However, the uncertainty created in NASA's 'faster-better-cheaper' approach after the failed Mars Climate Orbiter (1998) and Mars Polar Lander (1998) and subsequent cancellation of the Mars Surveyor Lander has delayed progress in Mars research. Since 2000, the Johnson Space Center has managed almost all of NASA's developments in ISRU technology. Under JSC's lead, hardware development models of sorption pumps and zirconium high-temperature electrolysis cells were set up and successfully ground-tested. End-to-end (ground) testing was performed on a Sabatier reactor/water electrolysis development model connected to a liquefaction and storage system.

The culmination of the ISRU research so far is the establishment of a flight experiment Mars In-situ propellant production Precursor (MIP), originally assigned to the 2001 Mars Surveyor Lander and which may now be manifested on a modified lander in 2003. The 8.5 kg experiment will demonstrate the carbon dioxide collection and compression step (sorption pump) and then the production of oxygen in a (zirconium oxide) ceramic high-temperature electrolyser cell.

3.3 ISRU in Japan and Russia

It appears that little lunar or martian ISRU research has been performed in Japan or Russia. However, Japan has published many articles specifically addressing civil engineering issues on the Moon using indigenous materials and the mining of helium-3.

4 European Technology Programme

The TRP activity on lunar oxygen processing is described in Section 3.1 of Annex 5. As mentioned there, significant synergy may be expected with the development work done in life support, specifically in air revitalisation.

5 Justification and Rationale

The major ISRU driver for any mission beyond the Moon is the saving of mass. To send to Mars all the materials required for a human crew and their return requires a (non-existant) very large launcher. Each tonne sent to Mars and returned to Earth requires 4 t in low Earth orbit. Based on the NASA Mars reference design mission, an upload mass of 60-90 t would be required merely for the return propellants and the life support consumables (water, breathing air) for a 6-member crew. Ariane-5 can currently send only 7 t to Mars! It is estimated that a martian ISRU plant of the required capacity could fit on Ariane-5. Unless larger launchers are developed, the mismatch in required and available upload capability can be solved only by *in situ* resource utilisation.

6 Technology Road Map and Technology Programme Proposal

The envisaged roadmap for the development of ISRU technology and development of the end-to-end production plants is given in Fig. A6.1. It takes into account the ‘reference exploration phases for the definition of the technology readiness requirements’. The ISRU work performed so far is rather limited so it is proposed, in the short-term, to perform a 2-3-year extensive system study, followed by a 2-3-year critical technology development phase and culminating in a 2-3 year (critical) technology demonstration.

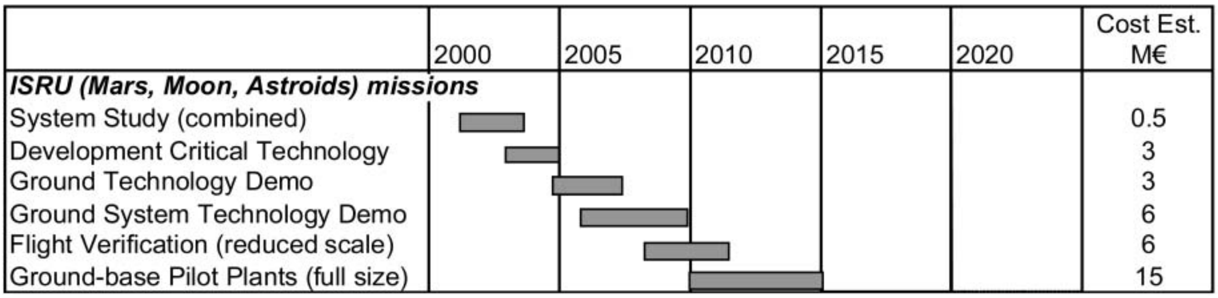


Fig. A6.1: In Situ Resource Utilisation – Technology Development Roadmap.

In the longer-term, end-to-end production plants must be established. If necessary, scaled-down performance testing of low-gravity critical items should be accompanied by verification flight testing. This should be followed by the development of full-scale end-to-end production plants as advanced breadboard models, to be followed by Phase-B/C/D. The order of magnitude costs indicated in the schedule (Fig. A6.1) reflect the combined activities. The planned system study is intended to provide a better estimation of the development costs.

The following activities are foreseen for the next 5-6 years :

— The system study covers all of ISRU's target bodies, although it may be subdivided into separate studies for Moon, Mars, Europa etc. The system study forms the basis for the overall development programme.
— A preliminary system design is established based on the preliminary mission requirements, indigenous feedstock characterisation, environmental conditions, etc. of the celestial bodies being considered for ISRU. For the different functions, candidate technologies are analysed. The selection of preferred technological solutions are supported with in-depth trade-offs and the critical technology identified for further development. The system study takes into account wherever possible interdisciplinary synergy (power, life support, propulsion, cryogenics, etc.). The major output of the system study is the critical technology for all functions of the ISRU systems to be considered for further development in the next study phase.
— The identified critical technologies (e.g. for Mars: ceramic oxide high-temperature electrolyser cells and long-duration cryogenic storage of hydrogen) are developed initially at laboratory scale followed by a self-standing technology breadboard acting, with the proper interfaces, as the technology demonstrator. The technology demonstrator is subjected to an appropriate test campaign.

The cost estimate given in Fig. A6.1 assumes that the appropriate technologies for all candidate missions will be developed in parallel. The system study addresses ISRU for all possible missions. If a specific mission is selected, development costs are lower and the estimate would be adapted accordingly.

Annex 7

Power

Annex 7 Contents

1 Introduction

The main objectives of the Power element of the Aurora programme proposal are:

— to prepare an improved concept for multi-kilowatt photovoltaic power generation;
— to prepare a new concept for a multi-kilowatt energy source and power conditioning technology;
— to prepare the technology for a fuel cell concept capable of storing energy for use by both base station and mobile vehicle.

Satisfying these objectives will meet the requirements of manned missions to Mars and unmanned missions to the jovian moons. For power generation and, particularly, photovoltaic technology, development and optimisation will focus on four main areas:

— enhancement of GaAs-based multi-junction cells;
— optical concentrator systems;
— inflatable solar array structures;
— thin-film photovoltaic modules.

For the nuclear power source, the study will be carried out considering the three main subsystems:

— the reactor itself and the nuclear shielding (the mass and other dimensions are almost constant at such high power levels);
— the power conversion system i.e. thermocouples, alternator, magneto-hydrodynamic (MHD) conversion;
— the cold source i.e. a radiator with dimensions that vary according to the reactor temperature.

For energy storage, the technology development will focus on demonstrating that multi-€ billion terrestrial fuel cells can be modified and integrated into regenerative fuel cell systems for Aurora.

2 Photovoltaic Technologies

2.1 Introduction

The goal is to prepare a concept for multi-kW photovoltaic power generation that meets the requirements of manned missions to Mars (up to 100 kWe on the surface) and unmanned missions to the jovian moons (up to 2 kWe for orbiters).

2.2 Technology Item Description

This technology development will encompass several areas, as outlined in the following paragraphs.

2.2.1 Enhancement of GaAs-based Multi-junction Cells

These solar cells are the best candidate for solar arrays for the cruise, orbital and surface rover phases of an exploration mission because of their very high efficiency and good radiation tolerance. GaAs-based multi-junction solar cells are manufactured using the Metal Organic Chemical Vapour Deposition (MOCVD) system and are grown on the Ge substrate. The currently available double-junction cells (GaInP2/GaAs/GaAs) have reached an efficiency of 24% at AM0, 25ºC, while triple-junction cells are predicted to reach up to 26%. In the near future, quad-junction cells (particularly if operated in a cold, low-illumination environment) are expected to reach 30%.

2.2.2 Optical Concentrator Systems

These systems are divided mainly into reflecting (mirror) and refracting (lens). For the reflecting systems, the V-trough concentrator that now provides a concentration ratio of about 1.65 seems to be the more attractive approach in terms of realisation, cost, influence of solar alignment and optical degradation during the mission. In its simplest form, each concentrator module would include a cell panel and two reflector panels forming a V-shaped structure when fully deployed. Refractive concentrators tend to be variations of Fresnel lens technology. Two concepts are briefly considered here :

— the Solar Concentrator Array with Refractive Linear Element Technology (SCARLET), developed in the USA, is a line-focus concentrator that uses arched refractive Fresnel optics to concentrate the incoming sunlight onto the cells. A secondary concentrator at the focus of the primary reflects rays onto the cell by total internal reflection, so it does not require a metallic surface. This system achieves a concentration ratio of about 7.

— a new refractive concentrator, developed by the Ioffe Physico-Technical Institute under an ESA/ESTEC contract, uses a Fresnel planar lens with a total internal reflection profile. It comprises a primary linear lens made of shock-proof UV-protective glass with a silicon refractive/reflective profile on the rear side, a secondary cylindrical lens made of quartz and additional linear photo-receivers providing off-pointing tolerance. The effective concentration is about 13.

2.2.3 Inflatable Solar Array Structure

This type of array structure, combined with thin-film cells, could enable missions to Jupiter using only solar power. This presents very important benefits in mass and cost reduction. The main important point is the use of new plastic materials for the array structure, allowing new configurations. Intensive analysis and tests are necessary to space-qualify such materials and architecture. Thin-film technology is the most important candidate for the cells. The compatibility between the structure and cell materials must be optimised.

2.2.4 Thin-Film Photovoltaic Module

Here, the key advantage being sought is significant cost reduction for the photovoltaic module at the expense of conversion efficiency. Thin-film solar cell technology that can be mass-produced at relatively low cost will likely be:

- amorphous silicon (α-Si) deposited on flexible polymer substrates providing 12-15% efficiency;
- polycrystalline structures based on copper indium diselenide (CIS and its CIGS alloys), characterised by an efficiency of about 15%,
- cadmium telluride (CdTe), with an efficiency of 10-12%.

2.2.5 Low-Intensity Low-Temperature (LILT) Silicon Cells

These solar cells have been developed and qualified by ESA for the Rosetta mission to cope with the severe temperature and illumination environment. Their use for specific exploration missions (e.g. Europa) could imply optimisation or dedicated qualification for a severe radiation environment.

Finally, it is important to underline the following points:

- the technology development will focus on the delta activities aimed at the exploration mission requirements, and will be harmonised with the general research & development programmes;
- the development of each photovoltaic technology will focus not only on the photovoltaic components but also on the support structures, in particular on the thin-film technology;
- a general study at system level will identify the specific mission requirements for the photovoltaic technology development activity.

2.3 Status

Although not as advanced as the USA, European companies are vigorously pursuing the photovoltaic developments described above. As a result, they are improving their competence in producing high-efficiency solar cells, cost-effective thin-film solar cells and concentrator array systems. The first European dual-junction GaAs solar cell will become generally available in late 2001 for commercial space use.

The two main industrial organisations in Europe for developing solar cells for space application are ASE in Germany and CESI in Italy. The USA has conducted extensive development of high-efficiency GaAs cells, and triple-junction devices are now readily applied to its government and commercial space programmes. Additionally, the SCARLET solar concentrator system was developed for and flown on the Deep Space-1 mission. Both Russia and Japan have produced GaAs single-junction cells in the past but are not as far advanced in this technology as the USA. Furthermore, Japan has achieved a good level of maturity in thin-film technology, even if only in terrestrial applications.

2.4 European Technology Programmes

A contract including initial development and limited production of triple-junction GaAs cells and array is in progress under TRP funding. Contracts involving the characterisation of cell materials and components and assembly technology for solar arrays are foreseen within TRP and GSTP. Some research & development projects on thin-film cells and solar arrays will also be carried under TRP funding. The design, development and qualification of a concentrator solar array are planned within ASTE, although it is optimised as a high-power array for geostationary telecommunication satellites. There are no development efforts underway for inflatable solar array structures or their interfaces with the thin-film photovoltaic module.

2.5 Justification and Rationale

Although planetary exploration beyond Jupiter is probably not feasible without some form of nuclear power source, photovoltaic technology is a strong candidate for transportation and orbiter-based research out to the jovian system. This has the advantage of offering both a cheaper solution and easier social/political acceptance than a nuclear source. It would also allow Europe to be active in planetary exploration while the nuclear option for manned landings and deep space exploration is in development.

2.6 Technology Roadmap (Next 30 Years)

The development of high-efficiency and low-cost solar cells and arrays requires:

- building on the current multi-junction GaAs initial development activity, in order to increase the number of active junctions and thus the efficiency of the solar cells;
- evaluating various solar concentration techniques that will enable solar power generation to satisfy mission requirements up to Jupiter orbiters;
- vigorously pursuing the development and exploitation of thin-film solar cell technology to make solar power more financially attractive;
- designing and developing inflatable solar array structures to allow the ready deployment of large arrays in space and also potentially on the martian surface.

2.7 Technology Programme Proposal

The schedule and budget for initial technology activities are listed below.

Phase 1: 1 year (July 2003 – June 2004)
Cost: €0.2 million in 2003, €0.8 million in 2004)
Research into state-of-the-art GaAs and thin-film solar cells.
Feasibility evaluation and prediction of cell thermo-optical and electrical parameters.
Feasibility study on solar concentrator concepts and inflatable solar array structures.
Identification of required critical developments and technology.

Phase 2: 2 years (July 2004 – June 2006)
Cost: €1.25 million in 2004, €2.5 million in 2005, €2.5 million in 2006)
Production of pilot production lines for multi-junction GaAs and thin-film cells.

Characterisation of such cells under Earth-orbit and LILT conditions likely to be experienced at Mars and Jupiter.
Breadboard definition, manufacture and test of a solar concentrator system.
Breadboard definition, manufacture and test of an inflatable solar array system.

3 Nuclear-Based Power Technologies

3.1 Introduction

The goal is to prepare a new concept for a multi-kW energy source and power conditioning for future Solar System exploration, meeting both manned and unmanned mission requirements. A robust nuclear power source is essential for planetary surface life support/exploration, activation of *In Situ* Resource Utilisation (ISRU) processes and powering unmanned space transportation systems. A power level of 100 kWe is projected, which translates to a thermal power of 0.2-2 MW (depending on the conversion process).

3.2 Technology Item Description

A nuclear power source consists of three main subsystems:

- the reactor itself and the nuclear shielding, for which the mass and other dimensions are almost constant at such high power levels;
- the power conversion system i.e. thermocouples, alternator, magneto-hydrodynamic (MHD) conversion;
- the cold source i.e. a radiator with dimensions that vary according to the reactor temperature.

Reactor cooling by liquid metal either directly or with heat pipes that can withstand very high temperatures (1400K for lithium) is a very interesting solution in the hundreds of kWe range because it offers reduced size and mass for the radiator.

One of the big advantages of this type of power source is its versatility since each of the subsystems identified above can be developed independently. An initial solution based on existing technology (e.g. thermocouples) can be incrementally optimised as, for example, turbine or radiator technology make progress.

3.3 Status

European companies have expertise in building nuclear reactor power plants and submarine reactors. Plants up to 5000 MW_{th}: Framatome ANP (F/D), British Nuclear Fuels (UK). Submarine reactors up to 300 MW_{th}: Technicatome (F). ASI has conducted a study into the Fission Fragment Nuclear Thermal Propulsion System ('Rubbia's Engine'). At the consultant level are AEA (UK) and Lahmeyer International (D).

The USA has worked on various Nuclear Thermal Propulsion (NTP) systems, mostly at the study level, but have also built hardware such as

KIWI, PHOEBUS and NERVA Solid-Core NTP Systems. Key companies are Westinghouse, Brookhaven National Laboratory, Sandia National Laboratory and General Electric. In the area of space reactors, the USA has built SNAP-10A (1965) and worked on the SP-100 study during the Strategic Defense Inititiative period. Key companies are Westinghouse, Brookhaven National Laboratory, Sandia National Laboratory and General Electric.

Russia operates many nuclear power plants, produces ^{238}Pu for radioisotope thermoelectric generator (RTG) purposes and has launched various nuclear reactors into space such as: ROMASHKA, RORSAT and TOPAZ. Key companies are the Russian Institute of Physics & Power Engineering (IPPE), Krasnaya Zvezda State Enterprise and Luch Scientific Production Association. Japan also operates numerous nuclear power plants and is pursuing an active research policy into fusion reactor technology.

3.4 European Technology Programmes

An initial conceptual design and technology identification activity to the value of €60 000 has been established within the current ESA General Studies Programme.

3.5 Justification and Rationale

One of the key issues to be solved for intensive scientific exploration out to Mars – and certainly further from the Sun – is the energy source. Solar energy becomes progressively insufficient beyond Jupiter. Radioisotopic sources are typically used for power levels below 1 kW and new power sources (fusion, antimatter, etc.) will not be available for operational application within the immediate future. Fission-based sources are therefore the solution to satisfy the demands of various deep space missions requiring power levels of at least 100 kWe, such as interplanetary propulsion and surface exploration. Such a level offers wide possibilities for electric propulsion, scientific exploration, life support and ISRU.

3.6 Technology Roadmap (Next 30 Years)

The technology is required to develop a liquid metal nuclear reactor meeting two basic requirements:

- a modular and versatile concept to deliver >100 kWe whatever the conversion system (that translates to 0.2-2 MW thermal power) together with the radiator;
- application as an energy source to a spacecraft or manned planetary exploration.

MHD power conversion is a process that converts the kinetic and thermal energy of ionised gas directly into electricity. The basic principle involves passing a flow of ionised gas through a duct containing a magnetic field perpendicular to the gas flow. An electric field is generated in the plane perpendicular to both the gas flow and applied magnetic field and, by positioning electrodes within the gas flow, electrical power may be extracted. Relatively high efficiencies (30-50%) have been estimated for this type of converter, with the limiting factor being the temperature required for the ionised gas.

This concept has already been demonstrated terrestrially and it would appear to be the most appropriate in terms of affordability, reliability, efficiency and global system performances in comparison with concepts such solar heat concentration and thermoelectric conversion. A study group consisting of French and Belgium companies and universities (Technicatome -Liège / Alcatel ETCA - CSL- University of Liège) prepared files for study and development of this subject.

3.7 Technology Programme Proposal

The schedule and budget for initial technology activities are listed below.

Phase 1: 3 years (July 2002 – June 2004)
Cost: total of €2.4 million (€0.3 million in 2002, €0.6 million in 2003, €0.6 million in 2004, €0.9 million in 2005)
Research into the state-of-the-art.
Feasibility evaluation and identification of thermal and electrical parameters.
Simulation and generation of mathematical models.
Identification of critical technology.
Initial definition of an overall architecture.

Phase 2: 3 years (July 2005 – June 2007)
Cost: total of €5.1 million (€1.6 million in 2005, €3.5 million in 2006)
Development of critical technology.
Finalisation of global architecture.
Breadboard definition.
Manufacture and test of a simulator system.

Additional activities must be expected for the 2 years after 2006, at a total cost of about €2.5 million.

4 Energy Storage

4.1 Introduction

The goal is to prepare the technology for a fuel cell concept capable of storing energy for both base stations and mobile vehicles in a manned and unmanned exploration initiative. The technology development focuses on demonstrating that that multi-€ billion terrestrial fuel cells can be modified and integrated into regenerative fuel cell systems for Aurora. Depending on the required power levels, the electricity can be provided by nuclear generators, regenerative fuel cells or batteries. Large stationary plants with long life requirements will most likely be nuclear, whereas smaller plants and, particularly, mobile units will be fuel cells and batteries. Nuclear sources are also excluded where radiation pollution is a problem.

A wide range of battery systems has been already qualified and is readily available. Rechargeable batteries are therefore not discussed in detail here, but a specific demonstration phase will be needed for each specific project. Regenerative fuel cells must be adapted from terrestrial developments, either from stationary power plants or mobile applications (electric cars, trains, etc). The required development time and funding would only be a fraction of that required, for example, in developing the Hermes fuel cells.

Fuel cells have been known since 1839, and until the mid-1980s were used extensively only in space and military applications. In the last 15 years, a tremendous effort has been made towards their commercialisation for terrestrial applications – and any upcoming space project can benefit from it. Current space technology is based on fuel cells with alkaline (KOH) electrolyte, but the terrestrial proton exchange membrane (PEM) technology is so far in the lead in terms of energy density.

4.2 Technology Item Description

For Solar System exploration, two distinct types of application are foreseen:

— a mobile Fuel Cell Power Plant (FCPP) using a PEM fuel cell, which works at a temperature below 100ºC and uses hydrogen and oxygen as reactants. This system offers higher efficiency and the reactants are regenerated via electrolysis of the product water, hence a 'regenerative FCPP' concept. This concept is especially valuable if water is available on a planet because then no reactants have to be transported from Earth; Europa appears to be a perfect candidate.

— the carbon dioxide atmosphere of Mars means that a stationary FCPP using a high-temperature, solid oxide fuel cell (SOFC) design can be built to any power level. Such a system can work directly with carbon monoxide, which is generated from the martian atmosphere by splitting carbon dioxide into carbon monoxide and oxygen. An infinite reactant supply is the available in principle. There is a variety of other fuels feasible, including all low molecular-weight hydrocarbons. Unfortunately, most planetary atmospheres cannot supply the reactants, which would have to be transported from Earth.

The technologies to be developed are fuel cell units in the range of a few hundred watts to about 25 kW to provide power for experiments, small packs for astronauts and larger units for mobile applications – all them incompatible with nuclear radiation. The energy densities of batteries may be too low. The fuel cells need to be rechargeable, so a combination with an electrolyser is required (regenerative fuel cell system). Electrolysers are well-established both for terrestrial and space applications but need optimisation in mass and lifetime. The presence or lack of gravity is not very significant (closed-loop systems).

4.3 Status

Several European companies have conducted fuel cell development. The activities emphasised terrestrial applications, stimulated primarily by the automotive and marine industries. To a lesser extent, there has been some space-related development. Significant activities are ongoing to demonstrate high-temperature fuel cells (SOFC) for remote power stations.

In the terrestrial field, companies with long experience include:

hydrogen/oxygen fuel cell (PEM-FC). Ballard Power Systems (with Daimler-Chrysler, D) and Ballard (CDN) are world-leaders in the field. Siemens-KWU (D) for submarine fuel cells. As a newcomer in this technology, Technicatome (F) expressed significant interest and submitted a roadmap.

high-temperature SOFC (relevant to carbon monoxide/oxygen fuel cells on Mars). Siemens (Westinghouse, D), Sulzer (CH), ECN (NL), study group at Technical University Graz (also involved in Mars studies).

In the space field (ESA activities):

Hermes spaceplane fuel cell, Siemens fuel cells and Russian (Buran) flight model fuel cell test evaluation.

Regenerative Fuel Cell System (RFCS), study contracts for Space Station, lunar rover and survey on Russian RFCS, in-house evaluation for space transportation (Crew Transport Vehicle).

The USA has worked extensively on various fuel cell systems, primarily for terrestrial electric vehicles and stationary power plants. Significant space fuel cell applications include Apollo and the Space Shuttle. Billions of dollars are being invested in the terrestrial applications, now including small portable units for military and consumer devices.

Although the US is the only nation currently flying fuel cells in space, the technology is old and still expensive. Russia developed a fuel cell system for Buran, many small systems for intercontinental missiles and some were tested on Mir. The cancellation of most military projects means there are no current space demonstrations of the technology. Japan is heavily involved in MW-sizes stationary power plants (SOFC), plus small portable units based on PEM technology for military and consumer devices.

4.4 European Technology Programmes

There are no European technology programmes currently underway for space applications. Recently, the TRP activity into product water removal (LGPS) was completed by DASA-Dornier. For many years, space electrolysers were developed by the same group originally funded by GSTP, then bilaterally funded with some DLR contribution.

4.5 Justification and Rationale

Fuel cell technology is essential for manned mobile planetary exploration because it offers an impressive energy density, allows recharging and, unlike the nuclear option, does not require that the power plant is physically remote from the crew or sensitive equipment. For the manned base stations, it also offers the advantage of providing an energy reservoir for peak power demands during daylight periods. Its use of natural atmospheric elements minimises the need for the expensive transportation of such consumables from Earth.

4.6 Technology Roadmap (Next 5-10 Years)

The goal is to develop a fuel cell concept exceeding 500 Wh/kg and meeting two basic requirements:

- a modular and versatile concept for integration into a system capable of delivering a total energy of 1-2 MWh;
- application as an energy source for emergency storage and/or load levelling at a manned base or alternatively as the primary energy source for a manned mobile vehicle and astronaut backpacks;
- the sizing covers the range from 500 W to about 10 kW.

PEM fuel cells would cover the Europa missions and the low-power end of Mars/Moon missions for mobile applications, while SOFCs would be developed for stationary plants and, if required, for larger rovers on Mars.

4.7 Technology Programme Proposal

The schedule and budget for initial technology activities are listed below (valid for both PEM and SOFC development), covering 5 years.

Phase 1: 0.5 years (July 2003 – December 2003)
Cost: €0.2 million in 2003)
Research into the state-of-the-art fuel cell technology.
Mission application definition.
Preliminary analysis of the space application constraints.
Feasibility evaluation and identification of electrical parameters.
Identification of critical technologies (materials, devices for fluid circulation/separation).

Phase 2: 1.5 years (January 2004 – June 2005)
Cost: €0.42 million (€0.28 million in 2004, €0.14 million in 2005)
Development of critical technology.
Finalisation of global architecture.
Preliminary design.
Manufacture and test of mock-up and scale models

Phase 3: 3 years (July 2005 – June 2008)
Cost: €1.02 million (€0.34 million in 2005, €0.68 million in 2006)
Detailed system definition.
Development of key components (fuel cell stacks and auxiliaries) for a multi-kWh system.
System integration and ground-based testing of a prototype fuel cell model.
Possible low-gravity testing such as onboard the International Space Station.

Additional activities for demonstration testing have to be foreseen in the 2 years after 2006 at a total cost of €1.02 million.

Annex 8

Propulsion

Annex 8 Contents

1 Introduction

The success of space exploration will largely depend on the availability of reliable propulsion systems capable of fulfilling strict new requirements such as enabling fast transfer times, large payloads, soft landing on planets and sample return. Some of the propulsion technologies presented in this Annex are the evolution in terms of size and performance of technologies already used on commercial and scientific missions (i.e. electric propulsion). In other cases, they are new technologies, existing today only at the concept or breadboard levels (nuclear-thermal propulsion, solar sails, etc.), or at the component level, possibly in the frame of other application areas (solar-thermal orbital transfer stages).

2 Electric Propulsion

2.1 Introduction

Traditional propulsion systems such as chemical propulsion have performed well in traditional near-Earth or deep space missions. But the relatively low energy they deliver for a given propellant mass imposes severe restrictions on missions requiring high ΔV. To reach the more distant planets, a chemically powered space vehicle must have very limited mass and make extensive use of planetary gravitational assists. To take advantages of these assists, mission planners must wait for launch windows. Electric Propulsion (EP) systems with high exhaust velocities consume much less propellant, allowing larger payloads and avoiding or reducing gravity-assist manoeuvres.

2.2 Technology Item Description

For exploration missions requiring short trip times and high payload fractions, a good compromise between thrust and specific impulse is a requisite for the propulsion system. For this reason, the best candidates among electric propulsion systems for this class of applications are the Hall-effect and gridded ion thrusters. More powerful versions than those qualified today are required for space exploration purposes. Another attractive candidate is the magnetoplasmadynamic (MPD) thruster, capable of even higher thrust densities. Their development is at a lower level, owing to the fact that they do not become attractive until power availability reaches 50 kW.

The major components of these electric propulsion systems are the:

- thruster(s),
- power conditioning, control and switching unit(s)
- propellant storage and distribution system
- thrust orientation mechanism (mission-optional).

Producing more powerful versions of these elements requires development to a new level of complexity.

2.3 Status

European systems (Hall-effect and gridded ion thrusters) are qualified or under development for power levels up to 4 kW. Europe's capabilities, alone or in collaboration with non-European organisations, covers all the elements. There is room for improvement in certain areas, such as propellant storage and distribution. Furthermore, the capability exists for testing these thrusters up to 10 kW of electrical power.

The major companies involved in or with potential for the development and testing of electric thrusters suitable for exploration are:

— Astrium (D, UK)
— SNECMA (F)
— DERA (UK)
— ALTA/Centrospazio (I)
— Laben (I).

Some of these companies also have capabilities for developing other elements of the EP system. Other companies with important roles to play in developing essential components include Alcatel/ETCA (B; power electronics) and Austrian Aerospace (A; orientation mechanisms).

In the USA, gridded ion engines developed and qualified by Boeing (formerly Hughes) at different power levels up to 4.5 kW have been used on several geostationary telecommunication satellites of the same company since 1997. In the scientific domain, the 30 cm ion engine on Deep Space-1, developed by NASA-Glenn, Hughes and JPL under the NSTAR project has demonstrated this EP technology for interplanetary missions.

In Japan, NASDA will launch the ETS-8 telecommunication satellite in 2003 with 25 cm ion thrusters for stationkeeping. Furthermore, Japan's Institute of Space and Astronautical Science (ISAS) is developing an asteroid sample return mission, MUSES-C, featuring a microwave-powered ion engine for primary propulsion in 2002. In Russia, Hall-effect thrusters at different power levels have been available for years and new models are being qualified, alone or in collaboration with western companies. A Russian mission to Phobos with a Hall-effect thruster is planned for 2004.

2.4 European Technology Programmes

ESA is funding, through TRP and GSTP, several activities for Hall-effect and gridded ion thrusters. The most important of these activities (under TRP) are:

— development (Astrium, UK) and qualification (in a test facility at ALTA, I) of the ROS-2000 Hall-effect thruster (up to 2.5 kW) for the next generation of European GEO platforms;
— design and development (under GSTP) of a modular Power Processing Unit for high-power Hall-effect thrusters (Alcatel/ETCA, B).

New TRP activities are being proposed to support development of new Hall-effect and gridded ion thrusters, offering higher power, variable specific impulse and longer lifetime.

The development of a 4-5 kW-class Hall-effect thruster has been initiated in France (SNECMA) under CNES funding. In the UK, DERA has developed a 3.5 kW gridded ion engine (T6) under BNSC funding. Astrium (D) is currently working, under internal funding, on the development of a 3 kW version of the Radio-frequency Ion Thruster (RIT).

2.5 Justification and Rationale

EP is a mission-enabling technology for space exploration because of its high ΔV capability. In addition, it is already considered to be strategic for commercial telecommunications, so every new development for application to exploration missions will also benefit future commercial applications.

2.6 Technology Roadmap (Next 30 Years)

EP is being used in telecommunication satellites for North-South Station Keeping (NSSK) and its level of maturity in the low- and medium-power range (0.5-4 kW) is high. These thrusters can be used for precursor exploration missions, such as a mission to the jovian moon Europa. ESA missions such as BepiColombo or the Solar Orbiter will use electric thrusters within this decade for the cruises towards Mercury and the Sun.

Some development towards higher power systems (4-10 kW) has been initiated in Russia and the USA for orbit-raising operations and interplanetary cruises. Building on its EP expertise, Europe is now capable of beginning developments that will provide full electric propulsion systems (Hall-effect and gridded ion) operating in the 10 kW range by 2010 or earlier. The systems developed within this framework will also find an immediate utilisation in the commercial space field. Ground-test facilities capable of performing characterisation and qualification of these thrusters are already available in Europe. In parallel to the development of these thrusters, advanced research in the area of MPD thrusters should be supported.

If a follow-on exploration initiative requires more powerful engines, ESA will be in a good position to begin development in the 30 kW range for qualification by 2015-20. This scenario makes it possible to consider intermediate missions using the propulsion system ready at any specific point in time, paving the way for a final mission within an exploration programme. The 30 kW level has been selected by considering a mission providing 100 kW to the propulsion system from solar panels. Three of these thrusters could be used, for example, to perform the cruise. Ground-test facilities capable of performing characterisation and qualification of thrusters above 10 kW will have to be developed in Europe.

In the event that Europe supports the development and use of nuclear generators on exploration missions, very high-power (above 30 kW) EP systems, including MPDs, can be developed in the period 2015-2030.

Table A8.1: Technology Programme Proposal for Hall-effect and Gridded Ion Thrusters.

Year	Activity	Budget (€k)	Note
10 kW Hall-effect Thruster and/or Gridded Ion Engine System(s) Development			
2002-2004	Pre-development activities	2000	Single activity common to Hall-effect thrusters and gridded ion engines. Part of the needed budget is covered by already approved TRP and CTP activities.
2005-2008	System development and intermediate models	(2 x) 15000	Hall-effect thruster and/or gridded ion engine system(s)
2008-2010	System full qualification	(2 x) 3000	Idem
30 kW Hall-effect Thruster and/or Gridded Ion Engine System(s) Development			
2009-2010	Pre-development activities	2000	Single activity common to Hall-effect thrusters and gridded ion engines.
2010-2011	New test facility development	8000	New test facility needed for engines > 10 kW
2011-2014	System development and intermediate models	(2 x) 20000	Hall-effect thruster and/or gridded ion engine system(s)
2014-2017	System full qualification	(2 x) 4000	Idem

Table A8.2: Technology Programme Proposal for MPD Thrusters.

Year	Activity	Budget (€k)	Note
> 50 kW Magnetoplasmadynamic thruster System(s) Development			
2003-2009	Pre-development activities	2000	Design, breadboarding and tests in pulsed mode. Design and breadboarding of other system elements.
2010-2011	New test facility development	10000	New test facility needed for engines >50 kW
2010-2013	System development and intermediate models	30000	
2014-2017	System full qualification	5000	

2.7 Technology Programme Proposal

The technology programme proposal presented here does not include demonstration missions, because a significant flight heritage will be provided by missions such as BepiColombo. Nevertheless, the use of EP thrusters is recommended for every exploration precursor mission in order to increase our experience of how higher power EP systems behave on future exploration missions.

The development steps and budgets shown in Table A8.1 apply both to Hall-effect and gridded ion thrusters. Depending on the results of a pre-development phase, common to the two technologies, the option exists to proceed with the development of only one type of thruster, depending on mission, technological and financial constraints. In addition to the activities in Table A8.1, Table A8.2 proposes further work within Aurora into MPD thrusters for future very high-power applications (possibly in combination with nuclear power sources).

3 Solar-Thermal Orbit Transfer Stages (STOTS)

3.1 Introduction

A solar-thermal orbital transfer stage (STOTS) is a highly promising candidate to perform bold scientific missions to the outer planets of the Solar System. In addition, the STOTS concept offers the unique advantage of being usable as a propulsion system in the first phase and as a sunlight-focusing device far from the Sun, providing electrical power and heat, thus avoiding the use of RTGs, which are not available in Europe. In other words, STOTS might offer the unique opportunity of enabling a scientific mission towards Jupiter/Europe or Saturn/Titan within Europe's present technical possibilities. For this reason, this type of mission is being analysed in detail within Phase-II of a running GSP contract dedicated to STOTS, to be concluded in 2001.

3.2 Technology Item Description

The power and heat source will use a solar panel backed by a radiator intercepting a variable percentage of concentrated flux depending on the Sun-spacecraft distance. The required flux-concentration factor is 25 at Jupiter's distance from the Sun, and about 80 at Saturn's distance. For an instantaneous collected power of 25 kW at 1 AU, this gives 1 kW power at Jupiter's distance, leaving 140 W (minimum) of electrical power and a few hundred watts of heating power.

The propulsive phase includes the following steps:

— launch into geostationary transfer orbit (GTO) or other elliptical orbit by Ariane-5;
— apogee-raising by firing STOTS at perigee (if required);
— when high Earth orbit is reached, a chemical (pressure-fed liquid hydrogen/oxygen) thrust arc near perigee injects the spacecraft into the interplanetary orbit;
— near-continuous thrust with STOTS to achieve the required ΔV.

The ΔV capability is estimated to be 5 km/s for STOTS and 1 km/s for liquid hydrogen/oxygen. This is sufficient for missions to Jupiter or Saturn:

— the chemical perigee burn provides an excess speed of 0.7 km/s i.e. sufficient to get directly beyond Mars;
— STOTS adds 3-4 km/s to reach an outer planet.

When a propulsive phase is required near an outer planet, the receiver and tank can be jettisoned to reduce the dry mass. A conventional chemical stage could be used for orbit insertion à la Galileo and Cassini.

3.3 Status

ESA is funding two parallel GSP studies with Aerospatiale Matra Lanceurs and SNECMA on the technologies and feasibility of a European STOTS. The two studies are in Phase-II for completion in 2001. In the USA, STOTS has been under development for more than 10 years, but a flight experiment under preparation has not yet flown.

3.4 European Technology Programmes

There are no current European technology programmes.

3.5 Justification and Rationale

STOTS offers the unique opportunity for scientific missions to Jupiter/Europa and Saturn/Titan within current European technical capabilities. All the technologies involved in the STOTS concept have extremely useful commercial applications.

3.6 Technology Roadmap (Next 30 Years)

Europe might benefit from the US results. A total of 5 years of development seems feasible for Europe before a flight experiment: 2 years of predevelopment/technology demonstration (for each major element), followed by 3 years of development. The flight experiment preparation could be performed in parallel to the development work. Three years might be needed to provide the first Flight Model for the flight experiment. The total time before flight is 8 years (sooner with increased funding). A year is required to perform the flight test and to analyse the first results.

3.7 Technology Programme Proposal

Note that the following budget figures still have to be confirmed by the STOTS GSP Study phase II results. Order of magnitude figures can be obtained from other programmes:

— for the foldable rigid solar concentrator, around €5 million would be necessary (based on the development costs of a large CFRP rigid deployable antenna with low mass per unit area and of the XMM-Newton mirrors for the high-precision reflective surface shape);
— for the low dry-mass fraction liquid hydrogen storage tank, around €4 million is needed (based on the development cost of the Ariane-5/ESCA liquid hydrogen tank);
— for the liquid hydrogen acquisition device based on thermodynamic venting around €2.5 million is necessary for ground tests;
— for the graphite receiver/heat exchanger, around €6 million is required (based on the development cost of a high-temperature space furnace, which has similar complexity but much higher mass and size).

It is very difficult to estimate the recurring cost of the Flight Model, although it will be small (€20-40 million) in comparison with the cost of the scientific spacecraft for the flight demonstration. A flight experiment could cost a minimum of 80 MAU, including launch (SMART-1 experience), if liquid hydrogen is replaced by liquid helium (smaller and simpler for launch) and the critical operational issues linked to the use of STOTS technologies are tested. A full flight experiment with liquid hydrogen would be more expensive.

4 Nuclear Thermal Propulsion

4.1 Introduction

The objective of a development project in Nuclear Thermal Propulsion (NTP) for Aurora is to prepare a new propulsion technology concept capable of meeting both manned and unmanned mission requirements, and providing superior adjustable levels of thrust and specific impulse, with high independence from solar energy resources:

- thrust level: more than 1000 N
- specific impulse: more than 1000 s
- independence from solar energy

4.2 Technology Item Description

Features of an NTP System

NTP systems, based on a fission or fusion process heating the hydrogen propellant, offer high thrust (the order of kN) and high specific impulse (the order of 1000 s and above), with the additional advantage of providing independence from solar energy. NTP is potentially superior to Nuclear Electric Power in terms of provided thrust levels.

Elements of an NTP System

- reactor core (fission or fusion) with the associated confinement (structural, inertial or magnetic), cooling and control systems, radiation shielding;
- power conversion system (MHD, dynamic, thermoelectric or thermionic);
- propellant system (additional fuel injection for adjusting thrust and specific impulse).

The development of the reactor core with its associated systems and of the power conversion system should be implemented in such a way to maximise their dual-use capability with any future nuclear power system.

4.3 Status

European companies have expertise in building nuclear reactor power plants and submarine reactors. Plants up to 5000 MW_{th}: Framatome ANP (F/D), British Nuclear Fuels (UK). Submarine reactors up to 300 MW_{th}: Technicatome (F). ASI has conducted a study into the Fission Fragment Nuclear Thermal Propulsion System (‘Rubbia’s Engine’). At the consultant level are AEA (UK) and Lahmeyer International (D).

The USA has worked on various Nuclear Thermal Propulsion (NTP) systems, mostly at the study level, but have also built hardware such as KIWI, PHOEBUS and NERVA Solid-Core NTP Systems. Key companies are Westinghouse, Brookhaven National Laboratory, Sandia National Laboratory and General Electric. In the area of space reactors, the USA has built SNAP-10A (1965) and worked on the SP-100 study during the Strategic Defense Inititiative period. Key companies are Westinghouse, Brookhaven National Laboratory, Sandia National Laboratory and General Electric.

Russia operates many nuclear power plants, produces ^{238}Pu for radioisotope thermoelectric generator (RTG) purposes and has launched various nuclear reactors into space such as: ROMASHKA, RORSAT and TOPAZ. Key companies are the Russian Institute of Physics & Power Engineering (IPPE), Krasnaya Zvezda State Enterprise and Luch Scientific Production Association. Japan also operates numerous nuclear power plants and is pursuing an active research policy into fusion reactor technology.

4.4 European Technology Programmes

There are no current European technology programmes.

4.5 Justification and Rationale

Current plans for a manned exploration of the Solar System are hampered by the inefficient propulsion systems available, featuring either values of high thrust/low specific impulse or vice versa. While the Moon is still in reach by means of chemical propulsion systems, Mars and the other planets are only accessible with extremely efficient high thrust propulsion systems if one wants to keep the round trip time within acceptable limits. An additional factor to be considered is the problematic of solar power generation at distances beyond of Mars.

4.6 Technology Roadmap (Next 30 Years)

The technology roadmap remains to be determined.

4.7 Technology Programme Proposal

Pre-development Phase (4 years, €0.5 million)
Study and evaluation of existing design (both fission and fusion based).
Simulation and generation of mathematical models for concept parameterisation.

Phase-1 (2 years, €1.5 million)
Identification of critical technology.
Trade-off study between fission- or fusion-based propulsion system candidates.
Breadboarding phase.
Decision for either a fission- or fusion-based propulsion system.

Phase 2 (3 years, €8 million)
Development of critical technology.
Finalisation of global architecture.
Engineering model definition.
Manufacture and test of simulator system.

5 Solar Sail Propulsion

5.1 Introduction

A solar sail is a flat, lightweight reflective surface that can propel a spacecraft using the momentum transfer of photons. The successful demonstration of this concept will enable very demanding missions. The main goal of this development programme is to solve the engineering problems associated with this technology and to test a representative concept in space.

5.2 Technology Item Description

The main technical challenges in solar sailing are to minimise the mass, maximise the surface area of the sail and control the dynamics of the system. In particular, some important activities to be done are: fabricate sails using ultra-thin films and low-mass booms; package sails in a small volume; deploy these lightweight structures in space; understand the dynamics and control the spacecraft. A flight demonstration of a model representative in power and size is very important. Large-surface deployment and control are the challenges.

5.3 Status

European companies and institutes (DLR, Kayser-Threde, INVENT, HPS, Telespazio, Contraves Spazio, Glasgow University, etc.) are involved in activities related to this technology. DLR with several companies and JPL are currently preparing a demonstration mission.

The USA has a community working on this technology with programmes led by NASA and JPL and carried out by companies such as Triton, Orcon, Astral and Boeing. In Russia, the Space Regatta Consortium (SRC) deployed a 20 m-diameter rotating solar reflector called Znamya. A series of flight experiments is planned for the near future. Several universities and institutes are also involved in activities related to this technology.

5.4 European Technology Programmes

ESA and DLR are funding a 2003 in-orbit deployment demonstration at a cost of €5 million. A first ground test was performed in December 1999 at DLR Cologne. A control demonstrator of a complete solar sail system is also envisaged but not yet funded. Funding of €30 million has been requested from ESA and DLR.

5.5 Justification and Rationale

A solar sail does not require engines or propellant, so the technology is suited to long-duration missions. Depending on the mission, a larger or smaller solar sail will be required to operate under different environments. The design therefore depends on the mission selected, and the critical technology may be different for different missions.

5.6 Technology Roadmap (Next 30 Years)

The technology roadmap remains to be determined.

5.7 Technology Programme Proposal

Phase 1 (2 years, starting after the results of the in-orbit deployment demonstrator are available, €4 million)

Mission analysis, feasibility study and evaluation of critical areas by analytical and testing methods. Manufacturing of breadboards is foreseen.

Phase 2 (3 years, €4 million)

Design, manufacturing and test of an engineering model capable of being used as an intermediate step in the development of flight hardware.

6 Planetary Ascent/Descent Propulsion Technologies

6.1 Introduction

Descent/ascent propulsion technologies for future Solar System exploration are suitable for sample return missions, compatible with strategies using ISRU propellant production (e.g. methane and carbon monoxide for Mars).

— thrust level range: 2-4 kN
— specific impulse level: more than 300 s
— independence from solar energy

6.2 Technology Item Description

Features of a Pump-Fed Propulsion System

Pump-fed propulsion systems, as currently used on the Space Shuttle and Ariane launchers, offer the advantage of a high-pressure combustion section (higher efficiency), while simultaneously keeping the pressure in the propellant feed system at a lower level, thus saving substantial propellant tank mass. An additional factor is the selection of the type of propulsion system. Careful selection of the propellant can achieve a good compromise between propulsion performance and ISRU requirements.

Elements of a Pump-Fed Descent/Ascent Propulsion System

— a Propellant turbo driven pump to increase the propellant pressure
— a descent/ascent high pressure engine with a thrust in the order of 2 to 4 kN
— high expansion ratio nozzle to take advantage of high engine combustion chamber pressure
— low mass propellant tanks (optional: tank staging)

6.3 Status

European companies (Alenia, FiatAvio, SNECMA, MAN, Astrium, EADS-LV) have competence in building high-thrust pump-fed propulsion systems (Ariane launcher). The USA has successfully built and flown various pump-fed propulsion systems on launchers such as Atlas, Delta, Titan, Saturn and the Space Shuttle. The key companies in this area are Boeing, TRW, Lockheed-Martin and Aerojet. Russia has built and flown various pump-fed propulsion systems for launchers such as Soyuz-Fregat, Proton and Energia. Japan has built high-thrust pump-fed propulsion systems for launchers such as the H2 and has some experience in low-thrust pump-fed systems. The key company is Mitsubishi.

6.4 European Technology Programmes

There are no European technology programmes underway.

6.5 Justification and Rationale

Current plans for scientific exploration of the Solar System foresee a detailed study of planetary resources, both by remote sensing and analysis of samples brought back from asteroids and planets such as Mars, Venus and Mercury. Some 500 g of martian soil, drilled from a pre-selected location, would provide an unprecedented wealth of information on the planet's history, geology and ISRU.

6.6 Technology Roadmap (Next 30 Years)

The technology roadmap remains to be determined.

6.7 Technology Programme Proposal

Pre-development Phase (3 years, €0.5 million)
Study and evaluation of existing design (both fission- and fusion-based).
Simulation and generation of mathematical models for concept parameterisation and dimensional/sizing analysis.

Phase 1 (2 years, €2.5 million)
Identification of critical technologies.
Development plan for candidate design.
Breadboarding and test.

Phase 2 (3 years, €7 million)
Development of critical technology.
Finalisation of design architecture.
Engineering design.
Manufacturing and testing of engineering system.

7 Tethered Systems

7.1 Introduction

Space tethers could bring significant improvements in terms of propellant mass because they are a propellant-less propulsion system. Envisaged applications could be Earth-escape trajectory insertion, deceleration for landing on the target planet and orbit capture and insertion from transfer orbit. Furthermore, a tether could be used to create artificial gravity for long manned interplanetary missions.

7.2 Technology Item Description

Momentum transfer by Mechanical Tethers (MT)
Transfer of momentum by cutting a tether between two satellites orbiting at different altitudes but at the same speed (orbiting at the speed of the centre of mass of the system). Transfer of momentum by cutting a tether between two satellites spinning around their centre of mass.

Lorentz force propulsion by Electrodynamic Tethers (ET)
Lorentz force for propulsion generated by interaction with the Earth's magnetic field of a current flowing through a conductive tether.

7.3 Status

The European background in tethered systems technology is:

MT: ready for demonstration flight (TeamSat was launched but not deployed);
ET: TSS-1 (Tether Satellite System) and TSS-1R (reflight) in cooperation with ASI and NASA. Broad expertise in Europe.

The European organisations with capabilities in tether are:

MT
Hardware: Alenia Spazio (TMM&M tether deployer), SENER (TMM&M tether deployer), Kayser-Threde (Rapunzel tether deployer), Delta-Utec (tether);
Ground testing: Alenia Spazio, Univ. of Padova (general testing);
Simulation: Alenia Spazio, Univ. of Stuttgart, Delta-Utec;
Theory: Astrium UK, Delta-Utec, Univ. of Padova, Alenia Spazio, Univ. of Stuttgart.

ET
Hardware: Alenia Spazio (TSS1 & TSS1R), Delta-Utec (tether);
Ground testing: CNR-IFSI (plasma testing), Univ. of Madrid (plasma testing), Alenia Spazio (deployment);
Simulation: Alenia Spazio, Univ. of Stuttgart, Univ. of Rome La Sapienza, Delta-Utec;
Theory: Univ. of Madrid, CNR-IFSI.

In the USA, the TSS-1 tether system and tether deployer were built by Lockheed-Martin. ATEX & TIPS were flown by Naval Research Lab. SEDS 1, SEDS 2, ProSEDS & PMG were flown by NASA Marshall. A network of mostly small companies and institutes are working in close cooperation with NASA Marshall on programmes for the development of space tethers propulsion. In Russia and Japan, expertise exists in the theory of dynamics and control.

7.4 European Technology Programmes

ESA
TMM&M (spool reel deployer);
TATS/TARGET (TMM&M capsule return demonstration mission on Progress, Phase-A/B);
GSTP-2: TSE (spool deployer capsule return demonstration mission on Progress/Foton, Phase-A/B);
Small studies: degradable tether material, failsafe tether design, bare tether collection probe;
Complex simulators: DATES, ETBSim and others.

National Agencies
ASI: TSS-1 & TSS-1R satellite;
DLR: Fiesta deployer;
NIVR/ESA: YES satellite.

Current activities

TSE (GSTP-2) being transferred to GSTP-3 for a demonstration mission on Foton.

Several small studies on electron collection, conductive tether stability and plasma chamber tests (ARCoP), tether lifetime (ESOC).

7.5 Justification and Rationale

In the framework of the Aurora Programme, tether technology can be mission-enabling and of a strategic value. Other space-related uses of the technology are artificial gravity, atmospheric research, coordinated multipoint sensing, deorbiting of defunct satellites (debris mitigation), Space Station stationkeeping and frequent capsule return capability.

7.6 Technology Roadmap (Next 30 Years)

1-5 years: the technology is ready for low-cost demonstration missions (piggyback): capsule return/orbit raising by momentum transfer (30 km tether), deorbit by conductive tether;

5-10 years: orbit raising by conductive tether, first applications in LEO (ET & MT);

10-20 years: first interplanetary missions;

20-30 years: manned missions.

7.7 Technology Programme Proposal

No additional development is necessary for MT; 1-2 years of tether development and related hardware is required for ET. A precursor programme with three small missions (< €5 million each) in LEO is proposed to validate the technology in space:

— a MT sample return;
— an ET end-of-life deorbit spent upper stage;
— an ET propulsive mission.

8 ISRU and Related Propulsion Technologies

8.1 Introduction

This propulsion technology involves systems capable of making use of propellant produced on the planets on which a spacecraft has landed instead of carrying the propellant from Earth. Two development areas are foreseen:

— propellant production technologies for Mars, Moon etc. (CO_2, CH_4, Ar, CO, O_2);
— propulsion systems capable of using these propellants.

8.2 Technology Item Description

Propellant production technologies

Issues related to this subject are covered by Annex 6 (ISRU) and are not part of this study.

Propulsion systems

— assessment on the use of existing propulsion systems with *in situ* propellants. Analytical and testing methods should be employed during this study. For example, the use of Mars propellants such as methane by chemical thrusters and take-off engines or argon and carbon dioxide by electric thrusters should be studied during this exercise;
— assessment of systems and logistical issues of propulsion technologies employing *in situ* propellants (filling, storage, assembly, redundancy, reliability etc.).

8.3 Status

Europe is currently making some effort mainly in the production technologies of *in situ* propellants. ONERA, CNRS, DLR, CIRA, TU Berlin and DERA are some centres working in this subject. In the USA, NASA, Loockeed-Martin and JPL are also working in production technologies. Russia has a good background in the field, having ground-tested methane engines (derived from flight-proven kerosene engines) at thrust levels from tonnes to several hundred tonnes. Japan has only dedicated some effort at the university level.

8.4 European Technology Programmes

ESA has contributed to this field with a study on a revitalisation system for crewed spacecraft. Production of oxygen with methane as a waste product was the main finding of the study. CNES is dedicating some effort on this subject through ONERA and CNRS.

8.5 Justification and Rationale

This technology has a strategic value: a reduction in the costly mass to be lifted out the Earth's deep gravity well. A synergy between production technologies of *in situ* propellants and life support engineering is very important. Production of gases such as oxygen is vital for manned missions.

8.6 Technology Roadmap (Next 30 Years)

— feasibility study (2003-2005);
— critical components research & development (2005-2012);
— demonstrations in space (2017);
— protoflight (2020).

8.7 Technology Programme Proposal

— feasibility study (2003-2005, €0.7 million)
— critical components research & development, first assessment (2006-2008, €1.3 million).

Annex 9

Robotics and Mechanisms

Annex 9 Contents

1 Introduction

1.1 Main Functions

The technology area of space automation and robotics (A&R) and mechanisms is essential for enabling the main functions described in the following sections of future Solar System exploration missions. Note that all of these functions can, in principle, be performed to various degrees of autonomy, depending on the feasibility and desirability of human operation on site or on Earth.

1.1.1 Docking/Berthing, Assembly, Inspection, Maintenance and Servicing

These functions will be needed during various phases of an exploration mission:

— For longer interplanetary missions, complex spacecraft or space structures will have to be configured in orbit because they cannot be launched at the same time. This applies to combinations of crew habitats and supply modules before the journey to a planet, and to an ascent spacecraft and orbiter before the journey back to Earth. As a minimum, this will require reliable docking or berthing of large modules, but probably also the unfolding/erection or assembly of large orbiting structures such as space power stations or antennas. Dedicated mechanisms or more flexible robot manipulator systems will be needed for this purpose. Once assembled, these complex structures must be periodically inspected, maintained and serviced during their potentially very long lifetimes.

— Once landed on the surface of the destination planet or moon, an infrastructure has to be established there (at the landing site or at a different base location). As a minimum, modules (e.g. habitats, stationary or mobile laboratories, greenhouses) have to be docked/berthed to each other. Larger structures for surface power stations, ISRU facilities, depots, shelters, communications relay stations and others will also have to be erected or assembled, and the resulting compounds will have to be periodically inspected, maintained and serviced.

1.1.2 Mobility

Mobility on the celestial body is one of the most essential and basic requirements. In general, we will have to provide

— *Mobility on the surface.* This includes mobility for deploying instruments and collecting samples (possibly with drilling/coring) in a local or regional vicinity of a landing site/base, unmanned scouting and exploration at larger ranges around a base, heavy cargo transportation, crew transport and mobile pressurised field laboratories. Varying technological demands will come from the local gravity field, size and type of vehicle payloads, the operating range and duration (considering diurnal and seasonal variations), the available communications and control infrastructure, the type of terrain to be covered (topology, but also availability of *a priori* maps), the presence of crew, etc.

— *Mobility beneath the surface.* For scientific investigations, as well as in preparation of base construction, underground operations will be required. This includes drilling/coring/probing for *in situ* analysis or sample return. The m technological challenges result from the properties (and predictability) of the subsurface material, from the required penetration depth (which may ultimately range up to several km), the required controllability and precision of the subsurface motion, the required preservation of the underground strata (including constraints on cross-contamination) and the available mass/volume/power.

— *Mobility above the surface.* This may be the preferred means of locomotion over large distances (e.g. for global reconnaissance, survey and exploration), or for *in situ* analysis and sample return from particularly inaccessible locations (e.g. the flanks of steep valleys on Mars). Depending on atmospheric conditions (e.g. density, but also the presence of winds), many possible concepts of floating or flying can be envisaged (see the types of aerobots described below). Mobility above the surface may even apply to bodies without an atmosphere, for example ballistic hopping on small bodies like comets, asteroids, or small moons.

1.1.3 Automation of Scientific and Technological Investigations

Robotic devices or mechanisms are essential to enable the logistics and fine motion of the various *in situ* investigations that have to take place on or below the surface of the celestial body:

— deployment and fine positioning of instrument sensors;
— handling of tools to obtain soil samples or to provide access to measurement locations (grinding, polishing, scooping loose material, picking up small rocks);
— logistics transfer of specimens among different stages of *in situ* investigation (e.g. feeding soil samples into analysis apparatuses or through a sample airlock for further processing in a pressurised laboratory).

1.1.4 Automation of *In Situ* Resource Development and Management

In the later stages of a surface base, more complex processes of *In Situ* Resource Utilisation (ISRU), plant cultivation and general ‘civil engineering’ infrastructure will need to be automated or at least supported by robotics or mechanisms. This can include:

— operation of tools for excavating/mining solid raw materials for ISRU;
— logistics transport of these materials among different stages of further processing;
— operation of the actual stages of *in situ* processing, refining, manufacturing, structure fabrication;
— manipulation and automation of processes for plant cultivation (‘gardening’);
— automation of processes for trash management (‘garbage collection and removal’).

1.1.5 General Support to Human EVA

Finally, during phases of human presence, astronauts will strongly depend on more or less intelligent tools to support and enhance their manipulative, sensory, but also cognitive capabilities in their strange and hostile work environment. This area of robotic EVA aids has not received much attention yet, but it is considered to be very important (comparable with recent or planned generations of aids for the physically handicapped on Earth).

1.2 Target Systems

The term 'robotics' used in this Annex requires clarification. While a general usage of the word refers to a 'robotic mission' or a 'robotic spacecraft' whenever no humans are involved, we here use a narrower definition. A 'robot system' denotes a mechatronic system that is able to perform a variety of manipulation, locomotion or more general actuation tasks of significant complexity in a flexible and controlled way. From these functional requirements, the main classes of target systems can be derived, and are described below.

1.2.1 Manipulation Systems

— long arms (stretched length of the order of 10 m) for in-orbit assembly. An example is the European Robotic Arm (ERA). This category will not be useful for surface operations because its slim design cannot support its own and payload mass under gravity.

— large gantry/crane systems for heavy-duty (the order of tonnes) cargo operations on planetary surfaces. To minimise the mass of these systems with respect to the mass of the cargo to be manipulated, the actual geometric and kinematic structure will be optimised for the type of tasks to be performed and the shape of payloads to be handled.

— short and dextrous arms (stretched length of the order of 1 m, with at least six joints providing all six degrees-of-freedom (but preferably with kinematic redundancy to optimise reach and handling capacity). This robotic equivalent of the human arm, equipped with a variety of (typically exchangeable) end-effectors (hands, tools, dedicated interfaces) at its tip, is the most general-purpose and versatile manipulative tool. It will feature prominently in all sorts of operations, from orbital servicing and inspection (possibly with one or two dextrous short arms mounted as an advanced end-effector on a long arm) to manipulations inside surface facilities to flexible devices on rovers or aerobots.

— tiny manipulation arms (micro-manipulators) are an interesting research subject, but their useful application in planetary missions is not yet obvious. Certainly, they fit the trend of general miniaturisation and could eventually be useful tools in the context of other micro systems.

1.2.2 Surface-Mobile Robots (Rovers)

Rovers can be classified into the following categories:

— large rovers (with a system mass of the order of 1000 kg and an operating range of 100s of km). Such large systems have been unaffordable after the first generation of Russian lunar rovers (Lunokhods), but will be needed again in surface bases as (unmanned) cargo transporters (possibly carrying a gantry/crane system) or as manned (pressurised) mobile field laboratories (typically equipped with short/dextrous arms).

- unmanned medium-sized rovers (minirovers) with a system mass of the order of 100 kg and substantial autonomy (operating range of 10s of km). This is the system of choice for regional exploration and scouting, able to return *in situ* measurement results and physical samples from the field.
- microrovers with a system mass of the order of (or well below) 10 kg and limited autonomy in control, communications and power supply (e.g. tethered to a lander). These very simple devices can dramatically enhance the return of early scientific landing missions because, with minimal own resource consumption, they can extend the reach of measurement instruments and bring them to the actual sites of interest (e.g. rocks in view of the lander). The Sojourner rover of NASA's Mars Pathfinder mission is an example of this type.
- tiny nanorovers of mass significantly below 1 kg represent the limit of what is technologically achievable nowadays. While they are more research subjects so far, swarms of such nanorovers have the potential for highly dedicated but distributed investigations with substantial system-level redundancy (many individual rovers can fail without degrading the overall mission performance of the swarm).

1.2.3 Underground Robots

These mechatronic systems address the requirement of mobility beneath the surface. They can be deployed and operated from a stationary base (e.g. a small lander of an early science mission) or from rovers (which allows them to visit several specifically selected sites). Typical classes are:

- automatic drill/coring systems operated from the surface. As soon as the required drill depth becomes larger (more than 1 m), single drills are prohibitive in terms of volume. For deeper drilling, robotically assembled and disassembled drill strings will have to be used. This creates a significant challenge of compact packaging and reliable control of the complex operations involved.
- rather than using a long drill string, small burrowing devices can be sent to completely disappear underground. These moles and penetrators offer the obvious advantages of small size and less complexity. Limitations exist in the permissible soil characteristics (typically only feasible for loose soil and not for hard bedrock), in their controllability (deflected by subsurface obstacles) and in their retrievability.

1.2.4 Flying/Floating Robots (Aerobots)

Depending on the atmospheric conditions, a variety of concepts can be employed for mobility above the surface of planets or moons:

- robotic balloons typically only have control of flight altitude (either active or passive, from induced temperature variations of the filling gas). Their horizontal motion is passive, provided by winds which can be very predictable depending on the altitude (as in the case of Mars). Attractive

Table A9.1: Mapping of Target Systems vs. Functions.

Robotic Functions vs. Target Systems	docking / berthing, assembly, inspection, maintenance, servicing	mobility on surface	mobility beneath surface	mobility above surface	automation of scientific / technological investigations	automation of in-situ resources development / management	EVA aids
long arms	x						
gantry / crane syst.	x					x	
short dextrous arms	x				x	x	poss.
micro manipulators	possibly				possibly	possibly	poss.
large rovers	x	x				x	
mini rovers	x	x				x	x
micro rovers		x				x	
nano rover swarms		x			possibly	possibly	
drill / coring syst.			x		x	x	
robotic moles			x		x		
Aerobots				x			
dedicated mechanisms / special. machinery	x		x		x	x	x

features are that they can potentially cover very long distances (global travel) including multiple intermediate landings with very high mass and energy efficiency.

- robotic airships are inflatable hulls with or without a rigid frame (blimp/ Zeppelin types), but with propulsion subsystems providing both vertical and horizontal acceleration. In terms of mass and complexity, they are between balloons and robotic aircraft.
- robotic aircraft of both the fixed-wing and rotary-wing (helicopter or autogyro) types have been proposed for Mars. At the expense of higher complexity, they could provide the maximum controllability of aerial mobility.

1.2.5 Dedicated Mechanisms and Specialised Machinery

These include essentially all other controlled mechanisms, which are tailored to very specific functions because the more general-purpose robot systems would be too complex or not suitable for the application. Specific types covered here are:

- docking/berthing mechanisms to couple spacecraft modules in orbit or on the surface.
- deployment/erection mechanisms for large structures like trusses, antennas, booms, solar sails (see Annex 8.5 on solar sail propulsion)
- tether deployment systems (Annex 8.7), controlled mechanisms for deployment and retrieval of mechanical and/or electrodynamic tethers.

— specialised machinery for automatic or astronaut-controlled excavation, mining, resource processing, refining, manufacturing, plant cultivation, etc.
— miniaturised, low-power, radiation-tolerant and extreme-temperature actuators for various other purposes.

1.2.6 Mapping of Target Systems vs. Functions

See Table A8.1 for the mapping of target systems against the functions required.

2 Technology Item Description

As evidenced by the complexity of the required functions and the typical target systems, Automation and Robotics technology is a system technology rather than a technology providing space subsystems or components. This can make it difficult to prepare adequate technology, because the eventual A&R systems will be very mission-dependent. This creates the classical chicken-and-egg dilemma for technology preparation: as long as no specific mission is designed (and approved) one cannot definitely assert the needed technology (and obtain funding for its development), but once a mission is approved it is far too late to start developing the critical technology.

Fortunately, it is possible to identify recurring building blocks (typically at subsystem level) for which innovative and capable technology can be developed. This is the approach taken by ESA for the past 15 years or so.

Analysing the target systems identified above, we can identify a relatively small number of technological building blocks on which the further discussion will focus. These building blocks are listed as the column headers in Table A9.2, which shows how they meet the needs of the target systems.

A few remarks on this technology building block approach:

— in general, the identified building blocks can be developed in a modular and scalable way which allows configuring them for the whole spectrum of expected application scenarios and target systems.
— a few target systems are still somewhat speculative (micro manipulators, nanorover swarms) because their need cannot yet be definitively asserted. On the other hand, their potential could be so large that it is unwise to ignore them. Here the approach is to provide 'technology push' in the form of early research & development and to introduce them as bona fide building blocks once they have sufficiently matured and their capabilities can be properly judged.
— a few other target systems and functions are so specific that no generic technology building blocks at subsystem level can be identified (e.g. the dedicated mechanisms and specialised machinery to automate very particular processes). They will necessarily have to be custom-developed once the mission requirements are available.

Table A9.2: Technology Building Blocks vs. Target Systems.

Technology Building Blocks vs. Target Systems	long arms (lightweight limbs, joint actuators + sensors)	short dextrous arms (limbs, joint actuators + sensors, end effectors, exteroc. sensors)	arm control s/s (h/w + s/w, o/b + o/g, robot vision)	larger, long-range rover locomotion concepts (wheeled, tracked, etc.)	small, short-range rover locomotion concepts (wheeled, legged, tracked,	advanced rover control s/s (h/w + s/w, o/b + o/g, incl. piloting + navigation sensors)	underground mobility concepts	aerobot mobility concepts	mechanisms (docking / berthing, deployment, actuators, tribology)
long arms	x		x						
Gantry / crane syst.	dedicated devel.		x						
short dextrous arms		x	x						
Micro manipulators		early R&D	early R&D						
large rovers				x		x			
mini rovers				x		x			
Micro rovers					x	x			
nano rover swarms					early R&D	early R&D			
drill / coring syst.						dedicated devel.	x		
Robotic moles						dedicated devel.	x		
Aerobots						(x)		x	
Dedic. mechanisms / special. mach.	dedicated mission – specific developments								x

— some sophisticated technology building blocks need to developed at the component level, such as advanced actuators (e.g. based on active materials using piezoelectric or shape-memory effects) or extreme temperature tribology items (coatings, lubricants) for dependable long-lifetime mechanisms.

The system character of Automation & Robotics also makes it highly multi-disciplinary. This implies that it will have to integrate subsystem technologies from other, more classical, space disciplines. Specifically this is the case for the following technologies, which are not considered here because they are the subjects of other parts of Annex D:

— miniaturised, low-power, radiation-tolerant and extreme-temperature avionics as the essential hardware platform for onboard controllers.
— software engineering technologies for reliable implementation of the (onboard) control software.
— telecommunications technologies (antennas, transponders) for compact, low-power communication from rovers or aerobots.
— power generation, conditioning and storage technologies for supplying the necessary electric and thermal power to rovers/aerobots/subsurface

robots (the power subsystem can be considered to be the most critical subsystem of an autonomous rover, certainly for longer-duration missions covering night periods).

With this background, Annex 9 outlines an approach to providing mature technological robotics and mechanisms building blocks in a timely fashion for use in the respective phases of an exploration programme.

3 Status

3.1 European State-of-the-Art and Centres of Competence

These are covered in Table A9.3.

3.2 Status Outside of European

These are covered in Table A9.4.

4 European Technology Programmes

4.1 ESA

ESA has been conducting systematic technology research & development into the directions of the building blocks identified here for some 15 years. The status achieved was summarised in Section 3. Table A9.5 provides a glimpse into this programme, indicating the funding source budget. For further details, refer to the proceedings of the bi-annual ESA-organised conferences on the subject:

— the ESA Workshops on Advanced Space Technologies for Robotics and Automation (ASTRA),
— the International Symposia on Artificial Intelligence, Robotics and Automation for Space (iSAIRAS),
— the European Space Mechanisms & Tribology Symposia.

4.2 National Developments

Table A9.6 captures the most eminent work done under funding from national space agencies in France, Germany and Italy. The rich variety of excellent institute research not directly related to space is not covered. Since 1994 or so there has been a judicious harmonisation and complementarity of the respective A&R technology development efforts between ESA and the member states. This is provided by the Advisory Group on Automation and Robotics (AGAR) which meets regularly to update the respective priorities and to discuss the research & development strategy. Recently, the general ESA technology research & development harmonisation initiative has also been conducted for the field of space robotics.

Table A9.3: European State-of-the-Art and Centres of Competence.

Technology Build. Block	European State of the Art	Centres of Competence
long coarse arms	EXCELLENT space qualified system available: ERA (ESA) no space operational experience yet	Astrium (D), Fokker (NL), HTS (CH), SABCA (B), Stork (NL)
Short dextrous arms	VERY GOOD space qualified system available: SPIDER (ASI) no space operatinal experience yet excellent research and industrial base	Alenia (I), Astrium (D), DLR (D), Tecnomare (I), Tecnospazio (I)
arm control	EXCELLENT space qualified h/w available (ESA) extensive o/b and o/g s/w available, partly to space standards (ESA, DLR) some space operational experience: ROTEX (DLR), ETS-VII (ESA, DLR)	Astrium (D), Astrium (F), DLR (D), FIAR (I), Fokker (NL), Krypton (B), Mecanex (CH), NLR (NL), Off. Galileo (I), SAS (B), Tecnomare (I), Tecnospazio (I), Trasys (B), many research institutes
Small rovers	VERY GOOD scalable design, high fidelity EM available of tethered tracked science rover: Nanokhod (ESA) excellent research base	DLR (D), EPFL (CH), Helsinki Univ. of Technology (FIN), Mecanex (CH), MPI for Chemistry (D), von Hörner & Sulger (D), VTT (FIN), other research institutes
large rovers	GOOD Mars and Moon designs, EMs available (CNES) work abandoned for lack of credible application scenario most critical: power generation s/s with high mass efficiency, long lifetime	Astrium (F), CNES, potentially car industry research centres
Rover control	VERY GOOD space qualified h/w available (CNES, ESA, DLR) much s/w available, partly to space standards (CNES, ESA, DLR)	Alcatel (F), Astrium (D), Astrium (F), CNES, DLR (D), SAS (B), many research institutes
Underground robots	VERY GOOD space qualified h/w available of short Mars drill (ASI) Mars design, EMs available of sampling mole (ESA, DLR) Mars design, EMs available of 2 m robotically assembled drill system (ESA) critical: much larger depths (no work yet in Europe)	DLR (D), Tecnospazio (I), VTT (FIN), potentially oil exploration industry research centres
Aerobots	GOOD Mars design available of balloon (CNES) early concepts available of Mars balloons, autogyro	Astrium (D), CNES, a few research centres
Docking / berthing mechanisms	GOOD EMs of docking mechanism developed for Columbus / Hermes in the past expertise may die out !	Alenia (I), Astrium (D), Sener (S), Verhaert (B)
Deployment mechanisms	EXCELLENT extensive space qualified h/w and operational experience available (antenna deployment mech., pointing mech., etc.) EM of tether deployment mechanism	Alenia (I), CASA (E), Contraves (CH), Delta UTEC (NL), Kayser-Threde (D), SENER (E),
Motors and actuators	VERY GOOD Space qualified hardware and extensive mission experience miniaturisation not yet fully implemented limited developments of active materials actuators continuity may be endangered due to loss of key supplier ETEL (CH)	CEDRAT (F), ETEL (CH) ??, RMB(CH), SAGEM(CH)
extreme temp. Tribology	EXCELLENT Mature FMs and operational experience for launchers limited to high temperature, short life time	ARCS (A), Balzers (CH), ESTL (UK), MAT (D), Praxair (D), VILAB (CH), Vito (B)

Table A9.4: Status Outside of Europe.

Technology Build. Block	US / Canada	Russia	Japan
long coarse arms	EXCELLENT • space qualified systems available: RMS, SS-RMS (CSA) • 20 years space operational experience (CSA)	VERY GOOD • space qualified systems built: Buran arm, Pelikan arm ? • some space operational experience on Mir • work essentially abandoned for lack of funding	EXCELLENT • space qualified system available: JEM-RMS • some first space operational experience on Shuttle
short dextrous arms	EXCELLENT • space qualified system available: SPDM (CSA) • space designs, technology developments and lab prototypes (NASA)	(no work known to us)	EXCELLENT • space qualified systems available: ETS-VII arm • space operational experience: ETS-VII • excellent research and industrial base
arm control	EXCELLENT • space qualified h/w and s/w available (CSA) • 20 years space operational experience, but only crew telemanipulation (CSA) • tech developments, lab prototypes (NASA)	GOOD • space qualified h/w and s/w built: Buran arm • no current work known to us	EXCELLENT • space qualified h/w and s/w available • space operational experience: ETS-VII
Small rovers	EXCELLENT • Mars and asteroid design available of wheeled micro rovers (NASA) • Mars operational experience: Sojourner (NASA)	GOOD • considerable developments and prototypes in the past • no space operational experience • now all but abandoned for lack of funding	(no work known to us)
large rovers	VERY GOOD • Mars and Moon designs available (NASA) • extensive terrestrial field test experience (NASA)	VERY GOOD • large Moon rovers built and operated in the 1970s • extensive development and field tests of Mars mini rovers in the 1980s • now abandoned for lack of funding	GOOD • first impressive Moon rover prototypes
rover control	VERY GOOD • space qualified h/w and s/w available (NASA) • extensive terrestrial field test experience (NASA)	GOOD • past work used technology which is now outdated • now all but abandoned for lack of funding	GOOD • first prototypes • very good research and industrial base
Underground robots	VERY GOOD • space qualified h/w available of short Mars, comet drills (NASA) • concepts and EMs available of robotic drill / penetration systems (NASA)	GOOD • extensive prototyping and testing of penetrators and moles	(no work known to us)
Aerobots	GOOD • concepts and prototypes available of Mars / Venus balloons, aircraft	(no work known to us)	(no work known to us)
Mechanisms	EXCELLENT • many systems operational in space	EXCELLENT • many systems operational in space	EXCELLENT • several syst. operational

Table A9.5: Technology Building Blocks (ESA).

Techn. Build. Block	completed developments	ongoing / planned developments
long coarse arms	all technology preparation leading up to ERA, e.g. SMS (TRP)	extensions of ERA for advanced assembly operations (TRP)
short dextrous arms	advanced joint actuators, end effectors, payload interfaces, bi-arm system concepts (TRP)	innovative lightweight arm and joints (TRP / GSTP3)
arm control	control development methodology, advanced o/b control algorithms and s/w, space design of computer and electronics h/w, advanced ground control s/s, sensors and s/w for robot and workcell calibration (TRP / GSTP)	algorithmic extensions, "light" o/b implementations, o/b telemanipulation, task planning aids (TRP / GSTP)
Small rovers	concepts and EMs of tracked, wheeled, walking Mars micro robots (TRP)	adaptations to Mercury environment (TRP)
large rovers	n/a (no applications perceived so far)	n/a (activity proposals were not approved due to lack of apparent applications)
rover control	end-to-end control of Mars micro rover, vision sensing, miniaturised cameras for low temperatures, radar sensor, Virtual Reality for ground user interfaces (TRP)	adaptations for Mercury (TRP)
Underground robots	drill and sampling mechanisms, robotically assembled drill / sampling system, penetrating mole (TRP / GSTP)	Mercury mole, advanced robotics probes (TRP), steerable mole (GSTP)
Aerobots	early concept for Mars autogyro (TRP)	first systematic study and concepts development
dock. / berth. Mechanisms	EM of Hermes-Columbus docking mechanism	n/a (use of existing non-European systems for ATV and CRV)
Deployment mechanisms	collapsible tube mast, wire antenna depl. mech. (TRP)	n/a
Motors and actuators	brushless micro motor, "smart motor", sensorless motor, space stepper motor, linear piezo actuator (TRP)	rotary piezo actuator (TRP)
Tribology	tribology application programme (TRP)	development of DLC solid coatings, self lubricated coatings for med. temps. (TRP)
System studies	ROLEX = robotics for lunar exploration (GSP)	AROMA = A&R for human Mars exploration (GSP)

5 Justification and Rationale

5.1 Rationale for Solar System Exploration

For many good reasons, Automation & Robotics and mechanisms have to be considered absolutely essential as enabling and strategic technologies in the framework of Solar System exploration:

— as shown before, robot systems or dedicated mechanisms will be essential elements of any true exploration mission, from early unmanned missions to later human expeditions and bases. They fulfil critical functions that cannot be met in other ways.

— because of its diverse and widespread roles, there will be ample market share for European A&R technologies even in international cooperations.

— Automation & Robotics enjoys a high priority in key ESA member states (Belgium, France, Germany, Italy, the Netherlands).

— as shown above, Europe has already achieved an excellent state of the technology, and with considerable less funding than was available for comparable developments in the USA, Canada and Japan.

Table A9.6: Technology Building Blocks (National Developments).

Techn. Build. Block	France (CNES-funded)	Germany (DLR-funded)	Italy (ASI-funded)
long coarse arms	• system work and testbed for SMS (ERA precursor) • no current or planned work		
short dextrous arms	• technology testbed for ISS internal arms (BAROCO) • no current or planned work	• ROTEX arm and gripper flown on Shuttle internal mission • EMs of highly integrated lightweight arm with advanced sensors, highly integrated multi-sensor grippers and hands, no space qualification efforts yet	• space qualified SPIDER arm, end effector • planned flight demonstration on ISS (EUROPA experiment)
arm control	• joint and arm control technologies for SMS • no current or planned work	• ROTEX experiment demonstrated variety of arm control modes • extensive work on advanced sensor-based control, advanced ground telemanipulation and sensor-based programming	• control s/w for SPIDER arm (planned)
small rovers		• prototypes of "tumbling" and wheeled micro rover (cooperation with Russia)	
large rovers	• prototypes and EMs of several wheeled medium / large rovers (cooperation with Russia)		
rover control	• extensive developments of vision-based rover navigation systems, incl. space qualification (cooperation with NASA) • test site in Toulouse: GEROMS	• little specific work on rover control (robot arm control work partially applicable)	
Underground robots		• prototyping and tests of robotic mole (cooperation with Russia, contribution to ESA's Mars Express)	• development of space qualified drills (cooperation with NASA and ESA's Rosetta)
Aerobots	• successful operation of 2 balloons on Venus (Russian Venera mission) • development of Mars balloon for failed Mars 96 mission (cooperation with Russia)		
Mechanisms	• Hermes docking mechanism		

— in a way, there is even an oversupply of excellent technology in Europe. The major problem so far has been the lack of applications (mission opportunities). This has created an unfortunate situation where many potent industrial partners have turned away from space applications as not lucrative and predictable enough.

— indeed, Europe enjoys an excellent research and industrial base in the field of robotics. Only very little of the potential available in industrial robotics or car industry and their research labs, in specialised machinery industry, and in university research has been devoted to space applications. An inspiring and high-profile planetary exploration scenario could mobilise outstanding capacities.

— like no other elements of a planetary exploration mission, robotic systems by their nature can provide high-profile and inspiring contributions, enthusiastically accepted, understood and followed by the general

public (see the gigantic public-relations success of NASA's Pathfinder/Sojourner mission).
— Automation & Robotics as a challenging multi-disciplinary system technology has the potential to stimulate excellent progress in a broad range of other key technologies such as advanced mechatronics, intelligent control, human-machine interfaces and telepresence.
— Automation & Robotics technologies developed for space exploration have wide potential for spin-offs to other space and terrestrial applications (see the following Sections).

5.2 Other Space-Related Uses

Progress in A&R technologies can directly benefit the following other space applications:

— flexible tending of payloads on platforms or in the pressurised modules of the ISS (using small dextrous arms).
— advanced exploitation of the ISS (short dextrous arms can enable novel science and technological investigations).
— in-orbit assembly of large space structures (large observatories, space power stations, interferometers, etc.) using large arms.
— support to planetary science missions (Mars, Moon, comets, Mercury, Venus, Titan, Europa, Phobos, etc.) by rovers, small arms, underground robots, aerobots.
— satellite servicing and preservation of GEO by dextrous arms for servicing, repair, disposal of incapacitated satellites, collection of space debris.
— commercial mining of asteroids for precious minerals.
— entertainment, as proposed by several recent commercial ventures to have theme park visitors command a Moon rover.

5.3 Terrestrial Spin-Offs

There are many terrestrial uses of robotics that have large similarities with space robotics and thus could benefit from significant progress achieved in space exploration programmes. So far, unfortunately, the balance of research & development spending has been leaning so much to the terrestrial side that space was the main beneficiary in the sense of technology 'spin-in'. The following mentions just a few, and all are believed to represent huge future commercial markets:

— advanced industrial robots for manufacturing, mining, agriculture, ship building.
— service robots (robots automating servicing tasks) for sub-sea applications (inspection and maintenance of oil rigs etc.), building construction, aircraft/ship/car maintenance (including refuelling), servicing and decommissioning of nuclear power plants, health care/home care/aids for the handicapped.
— field robots for disaster relief (including demining) and military applications.
— entertainment robots (e.g. robotic toys and pets that have started to become extremely popular).

6 Technology Roadmap

The following is an estimate of the necessary and possible developments of robotic and mechanisms technologies over the coming 30 years (Table A9.7). Of course, it is based on various assumptions that may be questioned and significantly revised, in particular to fit into the emerging phasing of the intended exploration missions. The main message is the following:

— several building blocks (e.g. ERA as a long arm, single short arms, the Nanokhod microrover for local science) are already at a very mature level and can be integrated into early flight demonstration missions immediately.
— for the more complex issues, much is presently available in terrestrial research labs and will have to go through space engineering phases.
— the performance of the initially demonstrated systems will be continually improved (offering more capabilities, needing fewer resources).

This lends itself perfectly to a judiciously staggered sequence of exploration missions, allowing quite spectacular successes early on and significantly reducing the development risk.

Table A9.7: Technology Roadmap for the Next 30 Years.

Techn. Build. Block	by 2005	by 2010	by 2015	by 2025	by 2030
long coarse arms	• ERA adapt. / evolution • ground test facilities	• in-orbit demo of robotic assembly (ISS) • adv. sensors / end effectors	• robotic assy. of large space structure (e.g. solar power station)	• large arms / cranes operate in unmanned Mars / Moon outpost	• operation of large gantry / crane system on Mars utility truck
short dextrous arms	• demo of single arm system on ISS • EMs of advanced dextrous hands • R&D into micro manipulators	• bi-arm system with adv. dextr. hands on ISS • signif. reduct. of mass / p/l ratio • altern. actuat. (e.g. piezoel., EAP) • ground demos of micromanip.	• intelligent short arms operational on Mars lander and rover (e.g. for sample return) • micro manipulators for Europa / asteroid mission	• short dextrous arms as tools in unmanned outpost infrastructure (ISRU, greenhouse, power station)	• short dextrous arms as tools on mobile pressurised lab, intelligent EVA aids
arm control	• demo of single dextrous arm control on ISS • developm. of bi-arm control • developm. of advanced hand control	• demo of bi-arm control on ISS • ground demos of vision-based reasoning and task control • control of micro manipulators	• intelligent control of multiple dextrous arms on Mars • control of micro manipulators on Europa / asteroid	• control of multiple coord. robot processes in outpost • signif. increase in intelligence and autonomy • synergistic task sharing humans/robots	• control of variety of robot tools in human outpost

Table A9.7 (continued): Technology Roadmap for the Next 30 Years.

Techn. Build. Block	by 2005	by 2010	by 2015	by 2025	by 2030
Small rovers	• FM of tracked Nanokhod for Mars / Mercury • EMs of nano-rovers • R&D into miniat. power supplies and avionics for long-term survivability	• first ops. of Nanokhod on Mars / Moon • FM of enh. Nanokhod as mobile base for shallow drilling • FM of nano rover swarm • enhanced integr. vehicle / payload	• oper. of enh. Nanokhod, nano rover swarm in Mars sample return mission • operation of nano rovers / nanobots on remote targets (e.g. Europa, asteroids)	• advanced micro rovers (increased autonomy, survivability) and nano rovers as part of unmanned Mars / Moon outpost	• micro / nano rovers as intelligent assistants for human exploration mission
large rovers	• EM of wheeled regional rover • ground test facilities established • terrestrial field tests (regional)	• regional rover for scouting on Mars • EM of large wheeled exploration rover • lightw. collaps. structures • terrestrial field tests (long range)	• exploration rover operational in Mars sample return mission • EM of large "utility truck" • terrestrial field tests utility truck	• regional rovers operational as part of unmanned Mars / Moon outpost • EM of mobile pressurised lab • terrestrial field tests mobile pressurised lab	• operation of utility truck, mobile pressurised lab on Mars / Moon
rover control	• FM of local micro rover control (via lander) • development of autonomous control • field tests • R&D into cooperative multi-rover control	• Mars demo of semi-auton. control of regional rover • hazard sensing + avoidance • auton. control of large explor. rover mature • control of nano rover swarms mature	• autonomous control of exploration rover demonstrated (Mars) • control of nano rover (swarms) demonstrated (Mars / Europa / asteroids) • control of large "utility truck"	• control of nano / micro / mini rovers operational in unmanned Mars / Moon outpost • control of mobile pressurised lab	• operation of utility truck, mobile pressurised lab control on Mars / Moon
Underground robots	• demo of robotic mole on Mars Express • EMs of robotically assembled drill systems (10 m) • R&D deep drilling (100 m)	• moles / drill systems on Mars (charact. / exobiology) • EM of deep drilling (100m) • R&D very deep drilling (1000 m) • R&D undergr. explor. of Europa	• underground robots operational on Mars sample return mission • field tests deep drilling • EMs Europa underground robots • EMs very deep drilling	• underground robots for ISRU • very deep drilling ops. on Mars (science, unm. base selection and build-up) • underground exploration of Europa	• underground robots have helped select and build up human outpost
Aerobots	• studies, trades completed on aerobot concepts • test facilities • EMs Mars / Venus balloons	• Mars / Venus balloons space qualified • EMs Mars aircraft	• first ops. of Mars aerobots for science, reconnaissance • increased control intelligence	• aerobots operate as part of robotic outpost	• aerobots as intelligent assistants in human outpost
Mechanisms	• TBD	• TBD	• TBD	• TBD	• TBD

7 Technology Programme Proposal (2002 – 2005)

A development plan can be directly derived from the roadmaps depicted above for the individual technology building blocks. Not all of the indicated achievements will have to be funded from Aurora; synergistic use will be made of already planned activities in the frame of the ISS or science missions. The schedule of the individual developments is tentatively indicated in the roadmaps, but will have to target the mission opportunities whose dates are completely speculative so far. It is almost impossible to give credible cost estimates at this point, because too many important issues are still open:

— what are the actually required functions and performances?
— what is the actual phasing and schedule of (technology precursor) missions?
— what is the scope of 'technology development' as opposed to actual development of mission and project elements?
— what industrial policy will be employed?

Overall, the main bottleneck is not seen in the missing technology or the inherent difficulty in establishing the technology, but the shortage of funding and the absence of any economy of scale. We are convinced that the schedules presented here could be significantly accelerated by increasing the annual spending, but this will hardly be realistic.

Under the assumption that only limited technology development funding (of the order of €4.5 million per year for robotics and mechanisms) and no first flight demonstration opportunity will be available until 2005, Table A9.8 proposes some important (but lower profile) early technology activities of generic nature with rough schedule and costing indications. This is seen as complementary to already planned activities in TRP, GSTP and ESA's Directorate of Manned Spaceflight & Microgravity. The activities proposed here are not funded anywhere else, but build on the status achieved in previous development work. This proposal is completely capped by the expected available funding envelope. It will not be sufficient to reach all the intermediate milestones (e.g. the 2005 status) described in the Technology Roadmap. The table also shows additional estimated cost of intensified technology developments (not only on the topics described under 'Initial Activity') in the 2006 – 2010 timeframe, including first flight technology demonstrations.

Table A9.8: Technology Programme Proposal (2002-2005).

Technology Building Block	Initial Activity	duration [yrs.]	cost until 2005 [M EUR]	add. cost 2006 – 2010 [M EUR]
system study	Refinement of application scenarios, system requirements, critical technologies and development planning for Automation & Robotics for planetary exploration. To build on and complement the running AROMA study which focusses on human Mars exploration.	1.5	0.5	1.0
long arms	Development of technologies (EMs of end effectors / tools / payload interface mechanisms), establishment of ground test facilities and ground demonstration of robotic assembly of large space structures. Building on ERA and current TRP activity, harmonised with XEUS assembly scenario. Aiming at demo on ISS in 2010 timeframe.	2.5	2.0	40.0
short arms	Development of an advanced dextrous (multi-finger) robot hand to EM level. To be compatible with ongoing arm developments (EUROPA, MISSISS / Robonaut), aiming at demo on ISS before 2010.	2.5	2.0	30.0
	Concept tradeoffs, design and early breadboarding of micro manipulators for planetary surface applications (small Mars stations, Europa, asteroids). Target: mass 1 kg, reach ca. 1 m, ca. 5 d.o.f.	1.5	1.0	
arm control	Development and ground test of advanced control schemes for bi-arm manipulation and dextrous multi-finger hand operation.	2.5	1.5	10.0
small rovers	First concept tradeoffs and analyses of nano robots (nanobots) for dedicated mobility on remote targets (Europa, asteroids).	1.0	0.5	12.5
large rovers	Concept design, breadboarding and terrestrial field tests of wheeled regional Mars rover for scouting and sample collection. To be harmonised with CNES and DLR work.	3.0	2.5	55.0
	Start the development of concepts and technologies for long-term rover survivability on Mars / Moon (miniaturised extreme-temperature high-efficiency power supplies, low-power avionics h/w, etc.)	2.0	2.0	
rover control	Development of semi-autonomous control s/w (autonomous o/b piloting, navigation with o/b sensors and ground support) for a regional Mars rover. Integrated field tests with locomotion h/w developed in parallel activity. To build up on and be harmonised with CNES work.	2.0	2.0	30.0
underground robots	Concept design and first breadboarding of robotically assembled and operated medium-depth drill system (> 10 m depth) for Mars exobiology application.	1.5	1.0	45.0
aerobots	Continuation of first TRP study: breadboarding and ground test of first aerobot concepts (e.g. Mars balloon).	1.5	1.0	30.0
mechanisms	Design, EM and test of shape memory alloy (SMA) actuator	2.0	0.5	25.0
	Design, EM and test of tbd other mechanism technologies	2.5	1.0	

Note that other mechanisms development activities are included in Annex 8 (Propulsion) (related to tether systems and solar sails).

Annex 10

Structures, Materials and Thermal Control

Annex 10 Contents

1 Introduction

The technologies needed to achieve success in exploration missions is to a very large extent dependent on the type of missions foreseen. Since specific missions or type of missions are not yet defined, certain mission model assumptions have to be made. Long-duration manned missions to Mars or other planets are assumed to include stations located either at certain points in space (Earth-Moon Lagrange points or others) or on the Moon. The life cycles of space vehicles is assumed to be several years (>10) and the life cycles of stations 10-20 years. Far-reaching missions will require assembling space vehicles at selected stations and, in the long-term, production of materials on the Moon or Mars will probably have to be considered. Also, autonomous unmanned craft, capable of exploring planets with landers, will be needed, but, to a certain extent, such systems are already being implemented by the Agency. However, some complementary technology tasks should be foreseen.

This Annex defines those structural and materials technologies not yet fully mastered in Europe but needed to perform missions of the kind described above.

For each structural sub-group (habitat structures, lightweight structures, etc.) the status of the technology is identified and new developments for the periods 2002-2006, 2006-2010 and 2010-2020 are proposed with preliminary order-of-magnitude costs indicated. Cost summaries are in Appendix A. It is assumed that more detailed system/mission studies will be continued after 2005, and that needed structures/mechanical technologies will be developed in parallel. The major mission milestones assumed are:

2002-2006
Initial technology developments

2005-2010
Unmanned demonstrator flights
Soft-landing (Moon,Mars, etc.)
In situ characterisation/resource utilisation test (Moon, Mars, etc.)

2010-2020
Robotic precursor missions
Sample return missions
Planetary lander missions
Man-rated missions (Moon)
Robotic outpost

Therefore, only structures technologies that could have a major impact on the feasibility of the to-be selected mission concepts are proposed to be addressed during the 2002-2006 period. Other important, but less critical, structures technologies, as well as the detailed development of critical technologies, will thus have to be performed after 2006. Most activities related to manned exploration missions are foreseen to start after 2005.

2 Habitat Structural Systems

2.1 Introduction

Planetary habitats could be manufactured as inflatable structures, deployable structures or even structures assembled in space from elements manufactured in space or brought from Earth. Another consideration is radiation shielding. Such facilities generally would require heavy structures most probably to be built on the planet in question. The identified technology areas are discussed below.

2.2 Technology Description

2.2.1 Module Structures

Whether for in-orbit stations or planetary bases, inflatable module structures offer deployed volumes large in comparison with the launch volume. The simplest inflatable items are airlocks and tunnels that would provide connection between rigid modules without requiring their accurate alignment. They would offer only a reduced set of services to provide e.g. controlled lighting and thermal conditioning. Maintenance hangars would be the next step in terms of complexity. They would provide an enclosure for shielding astronauts and hardware during scheduled maintenance and repair activities. For longer stays, they would need to offer more facilities like workstations and mounting systems, parts and tool restraint and storage, and micrometeoroid protection. The highest level of complexity would be achieved with structures for residential quarters/habitats and greenhouse structures providing all the life support functions.

The morphology of these facilities are based on the development of standard inflatable elements such as beams, 2D structures and frames, 3D truss structures, spheres and 3D enclosures. Furthermore, a key element in using flexible inflatable structures is the development of reliable connection techniques between the flexible and rigid elements.

The materials will have to be selected after investigation of their performance following long-duration exposure to the space environment (possibly years under deep space conditions), including ageing, thermal cycling and radiation exposure. There is a need for advanced numerical tools to study both the folding techniques and the in-orbit or on-ground (for planetary missions) deployment dynamics of these complex structures.

2.2.2 Assembly/Joining Technologies (Welding, Fastening, Others)

As a preliminary condition for efficient assembling, modular structures will have to be designed and evaluated. Owing to the hostile space environment, most assembly will be performed by remote manipulator arms and a limited number of EVAs. A key element will be the development of a very limited number of standard coupling interfaces. Pressurised modules will require one type of interface, while truss structures will require another. Self-locking interfaces will be necessary for time-efficient integration. As some external payloads will require platform-type supports, development of standard panels to be plugged on truss structures will be needed. The assembly of large pressurised modules will require welding in space. Techniques such as electron beam welding and laser welding have to be explored to adapt them to the local environment and to the size and type of elements to be assembled. The long exposure to the space environment requires a thorough investigation into the effects of time, thermal cycling and radiation on materials, joints and mechanisms.

2.2.3 Metoroid Impact Protection Technologies.

Unless the stations are located in Earth's immediate vicinity, space debris will not be a dominant factor. Meteoroids will be the main driver for long-duration missions to the Moon or Mars. The large difference in impact velocities between space debris and meteoroids will require assessment of the feasibility of experimental techniques to reach impact velocities in the velocity range 15-30 km/s. As the assembly of a station on the Moon or far from LEO requires *in situ* work, there is *a priori* no constraint limiting the shield spacing. It is an opportunity to explore shields with large stand-offs (distance between the front bumper and the main structure). The long lifetime of the station requires tests with large projectiles (5-20 g at around or above 10 km/s). For space vehicles, deployable or inflatable shields must be explored. New materials like foam will be characterised for the envisaged applications. To minimise space pollution and dust spreading on the Moon, materials limiting the amount of secondary ejecta should be considered for the front bumper.

2.2.4 Maintainability/Repairability/Inspectability, including Health Monitoring

Space exploration missions, manned or unmanned, must be based on very reliable vehicle and infrastructure systems, capable of a high degree of autonomous operation. In particular, the infrastructure for manned missions will need to be optimised in terms of maintainability, repairability and inspectability. The ISS is in it self complex from this point of view, but moving further from Earth even in a small spacecraft increases the complexity many fold. Many specific technologies in this area need to mastered in order to achieve successful missions. Some are directly linked to the structural concept selected (e.g. inflatable structures), but others are quasi-independent.

Critical structures must be constantly monitored through a health monitoring system (HMS). Health monitoring is the fully automated and fully autonomous monitoring of the condition of a vehicle's system or subsystems, permanently integrated within the system. This includes both the definition of appropriate sensors and the development of data-handling logics. For areas where potential damage is indicated, or simply for routine checking, non-destructive inspection techniques must be available. This includes the development of accurate techniques, based on known terrestrial approaches, as well as possible implementation procedures (man-operated, automatic, internal/external). Finally, in case damage is identified, repair techniques must be available. The repair approach could include some of the assembly/manufacturing technologies mentioned above (e.g. welding) for larger problems, but should include repair techniques for smaller damage, such as caused by the crew or meteroid impacts.

2.3 Status

The development of modular structures will require expertise in pressurised modules and related interfaces. Such expertise is available in Europe at Alenia (Italy) and Astrium (D).

For inflatable habitats, the NASA Johnson Space Center has been working on the TransHab project for some years, making significant progress. In Europe, extensive work has been done on inflatable reflector structures; Contraves (CH) must be considered one of the world leaders in this domain. However, very little effort has gone into inflatable modules. Astrium (D) and Contraves (CH) have initiated studies on the topic, and have made an unsolicited proposal to ESA for the development of a demonstrator structure.

The joining of large truss structures has been studied extensively in the USA, and is currently being implemented for the ISS. However, the development of larger modular habitat-like structures still need to be performed both in Europe and the USA.

Russia has studied in-orbit welding, and has apparently made good progress. Very advanced welding techniques are currently used in Europe, also in launcher and spacecraft manufacturing, but their transfer to space applications has not occurred. This is an area requiring special attention, possibly with international cooperation.

Impact shielding technologies are well established for protecting ISS elements, both in the USA and in Europe. Shields for Columbus, ATV and Cupola have been developed and tested in Europe. Test facilities are available on both continents, bu not for velocities above 10 km/s. Some developments on advanced shielding materials are under way in Europe, and attempts are being made to begin development of high-velocity impact testing (with CEG France). Some activities are expected to begin in the near future, funded through ESA's dedicated space debris budget, but a number of exploration-specific activities must be tackled in parallel.

Health monitoring systems have been studied in Europe and the USA for some years, but the technologies are still not mature enough to be used for exploration missions. Some progress has been made within FESTIP, X-38 and TRP. A small activity dedicated to a specific sensor development began in 2001, but no others are currently funded. Impact recognition and damage characterisation systems, originally foreseen for ISS but not yet implemented, are needed. Inspection systems to be applied in space (robot- or astronaut-operated) are currently not available.

2.4 European Technology Programmes

Module Structures

The deployment dynamics of structures offer some similarities with airbag inflation. The simulation of airbag deployment has been addressed in the automobile industry (ESI) and for scientific exploration like spacecraft intended for landing on nearby planets (Mars). The design and development of inflatable structures has been studied (Contraves inflatable antenna).

Assembly and Joining
With respect to assembly and joining, several GSTP studies have addressed the development of new lightweight inserts for sandwich panels with CFRP facings (DLR) and the associated design tools (Patria Finavicomp). GSTP studies have addressed the joining of large CFRP tubes (XMM-Newton type) where alignment is critical (Patria Finavicomp). Self-locking attachments have been explored within the European Robotic Arm project for the ISS (Astrium GmbH).

Meteoroid Impact Protection
Most of the basic technologies needed to design and verify the performances of meteoroid impact protection have been developed to support Europe's ISS participation. Two-stage light gas guns are available in Europe for accelerating 1-50 g projectiles at impact velocities around 6 km/s (EMI, CEG). Numerical simulation techniques have been validated to cover the high velocity range of impact conditions (10 km/s and above; Century Dynamics). Unfortunately, these techniques fall short of addressing the impact conditions expected from meteoroids at some distance from Earth. Expected impact velocities above 15 km/s will, in addition to full vaporisation of the material, possibly create incipient plasma and electromagnetic effects. Those questions have not been addressed in Europe.

Maintainability / Repairability / Inspectability / Health Monitoring
Health-monitoring studies in Europe are, as elsewhere in the world, mainly aimed at terrestrial applications (including aerospace) for composite structures. Methodologies and sensors, combining a process-control function and the subsequent health-monitoring function, have been developed. Reusable launch vehicle applications have been studied within FESTIP (Kayser-Threde, D; Contraves, CH), a new sensor development for cryotank application is in preparation (TRP), and advanced manufacturing applications will be part of a new GSTP programme with DMT (I). An acoustic emission monitor for impact damage was developed for Columbus (DNV, N), and a free-flyer inspection unit (Inspector) has been studied by Astrium (D).

2.5 Justification and Rationale

The above technologies are mostly intended for manned exploration of space. They are needed to prepare for the long-term presence of man on the Moon, which could be a first step toward farther exploration. Technologies like modular structures and self-locking attachments could provide new concepts for terrestrial public transportation.

2.6 Technology Roadmap (Next 30 Years)

The technologies presented above should be the objects of on-ground demonstration by the time the ISS is fully operational (~2005). In-space demonstration should aim at not later than 2010. Implementation in an exploration mission in Earth's vicinity (well above the ISS or possibly on the

Table A10.1: Technology Programme Proposal for Habitat Structural Systems.

2002-2006	1.1 M€
- Preliminary configuration studies (structural concept etc). (e.g. by Alenia/I, Astrium/D)	0.3 M€
- Development of numerical tools (large thin membrane structures). (e.g. by SAMTECH/B, ESI/F)	0.3 M€
- Initial development of on-orbit welding techniques (possible international cooperation) (2002) (e.g. by Astrium/D, Welding institutes/UK, F, et al., Alenia/I)	0.5 M€

2006-2010	9.0 M€
- Habitat configuration studies (structural concept, mock-ups) (e.g. by Alenia/I, Astrium/D)	0.5 M€
- development of numerical tools, materials, repair aspects etc. On-ground and possible flight demonstrations; (several industries from many member states can perform such tasks)	5.0 M€
- initial development of on-orbit welding techniques (e.g. by Astrium/D, Welding institutes/UK, F, et al., Alenia/I)	1.5 M€
- development of in-orbit welding demonstration hardware (e.g. by Astrium/D, Welding institutes/UK, F, et al., Alenia/I)	2.0 M€

2010-2020	12 M€
- development of numerical tools, materials, repair aspects etc. Qualification for flight	10.0 M€
- development of larger (sub-scale) habitat demonstrator structures	2.0 M€
- preparation of in orbit welding demonstration (cost will depend on the degree of international cooperation, launch costs etc)	
Beyond 2005-2006, the possibility of developing an inflatable habitat flight demonstrator, e.g. on the ISS, should be explored	

Moon) could be foreseen from 2015 or earlier, depending on when the flight demonstration is performed. Based on the acquired experience, strategies to send humans beyond the Earth-Moon system should be reevaluated and implemented in a thoroughly matured mission beyond the Moon by 2025.

2.7 Technology Programme Proposal

The following technology programme encompasses technologies needed to initiate an on-orbit demonstration phase during 2005-2010. The scope of the technologies will not in all cases be fully adequate for on-orbit demonstrations, but at a minimum the programme will develop the technologies to a degree of maturity sufficient to verify the feasibility of proceeding with the flight demonstration phase.

Table A10.2: Technology Programme Proposal for Habitat-Related Technologies.

2002-2006	**2.3 M€**
- evaluation of high-speed impact test facilities, and facilities for tests with larger particles; (it is foreseen that this is complemented by several related activities to be initiated in the Agency and funded by a dedicated Space Debris budget) *(EMI/D, CEG/F)*	0.2 M€
- development of numerical tools for simulation of high-speed impact non-metallic materials; *(Century Dynamics/GB, ESI/F)*	0.5 M€
- initial development of a health monitoring concepts for manned spacecraft and habitat systems; + funding from other sources, e.g. RLV programme, TRP *(Kayser Threde/D, universities, ...)*	0.5 M€
- initial development of NDI methods (robot- and/or astronaut-operated) *(Astrium/D, MAN/D et al.)*	0.6 M€
- initial development of repair techniques for pressurised and other structures	0.5 M€

2006-2010	**4.7 M€**
- initial development of lightweight meteoroid shields for habitat systems (concepts supported by analysis and a limited test programme) *(EMI/D, Alenia/I)*	0.5 M€
- initial development of a health monitoring concepts for manned spacecraft and habitat systems; + funding from other sources, e.g. RLV programme, TRP *(Kayser Threde/D, universities, ...)*	0.6 M€
- initial development of NDI methods (robot- and/or astronaut-operated)	0.6 M€
- development of NDI demonstrator facility (ISS experiment possibly, e.g. use of ERA?)	2 M€
- development of a health-monitoring demonstrator system for possible implementation in a flight structure (TBD)	1 M€

2010-2020	**1.0 M€**
- detailed shielding concept development for selected missions.	1 M€

3 Large Lightweight Inflatable and Deployable Structure Technologies

3.1 Introduction

Future missions to deep space or to the Moon and planets will require large lightweight deployable and/or inflatable structures for applications such as large reflectors (including telescopes), solar arrays, solar sails and radiators. The identified technology areas are described below.

3.2 Technology Item Description

3.2.1 Large Reflectors

Future space telescopes and interferometers must be deployed on-orbit to provide the very large apertures required to resolve the planets of distant stellar systems. The performance of such instruments depends on maintaining the precision and stability of the deployed geometry with high structural efficiency. This means a large area maintained with optical precision with a minimal mass structure.

Bicurved reflective surfaces able to survive the effects of debris impact, charged particles and electromagnetic fields and with smart capabilities to correct their shapes need to be developed. Large deployable booms to support the reflective surfaces based on composite or metal shells combined with inflatable technologies must also be available. Other important contributions to loss of accuracy are the friction and freedom in the joints; deployed instruments would change shape to the order of the required resolution. Joints with linear behaviour and no friction, based on shape-memory materials (such as piezoelectric materials), provide the required precision.

Deployment of this very large and light structure on the ground introduces the possibility of damage and fatigue, so testing and associated technology such as offload devices must be revised.

3.2.2 Solar Arrays, Solar Sails, Solar Reflectors and Shadow Shields

Most of the technologies required for large reflectors are applicable to solar arrays and solar sails.

Solar sails can propel spacecraft to 200 AU in 15 years. New membrane materials with reflective and emissive finishes, adequate film stress and a density of the order of 10 g/m^2 are required. Mathematical tools to provide confidence in the design and able to analyse buckling of such low-mass membranes, taking into account all the environment effects, are needed.

Solar array technologies will focus on thin-film solar cell developments. Rolled-up and boom technologies must be available. Solar reflector or concentrators with similar technologies as those of the large reflectors will be needed. Shadow shields may, for example, protect a cryogenic stage from the solar flux. From a structural point of view, they are similar to the applications mentioned above.

3.2.3 Other Deployable Structures

A spacecraft using nuclear-electric propulsion (NEP), carrying a small reactor of the order of 200 kWe, will dissipate a lot of power and therefore require very large thermal radiators.

3.2.4 Inflatable Structure Technologies

The inflatable technology required for applications such as large reflectors, solar sails, radiators and shields differs from that of habitat applications mainly in the really large structures and light loading. As for habitats, it will be necessary to develop structural elements like beams, masts and 2D and 3D frames to permit modular designs. Materials, including the space rigidising materials, will have to cope with the usual space environment: degradation of characteristics with time, thermal cycling and radiation effects.

Design numerical tools need to be developed to study both the folding techniques and the deployment dynamics. For in-orbit facilities, large flexible appendages will impose additional constraints on the spacecraft operations (attitude & orbit control). Dynamic stability must be assured through, for example, adaptive and smart structures.

3.3 Status

Inflatable space-rigidising reflector structures were developed in Europe by Contraves (CH) during the late 1980s and early 1990s. There were similar activities in the USA. However, adapting the developed technologies to the large structures required for solar arrays, sails etc. remains to be performed. This requires developments in materials, packaging and numerical tools.

For ultra-lightweight bicurved reflective surfaces with foldable capabilities, work has been performed in the USA for a CFRP membrane and, to a lesser extent, in Europe (and Georgia) for CFRP and ultra-thin nickel electro-formed membranes.

Large deployable booms have been studied in the USA and Europe (Sener, E; Contraves, CH; Astrium, D), but the technologies are far from flight ready.

For the large rolled-up solar arrays, some work has been performed in the USA, and a small ESA TRP activity is planned to begin in early 2002. For the large solar concentrators and large thermal radiators, work has been performed in the USA and Europe.

In all cases, the structural concepts are at a rather early stage and require significant developments.

3.4 European Technology Programmes

There is currently DLR activity in solar sailing. ESA will initiate a TRP activity on inflatable structures in 2001, aimed at developing the building blocks common to and necessary for the different identified applications and also at building a small circular demonstrator structure. This structure

Table A10.3: Technology Programme Proposal for Large Lightweight Inflatable and Deployable Structures.

2002-2006	**5.05 M€**
- Further development of inflatable structure technologies (materials, folding techniques, interfaces/joints, stability, smart control etc); *(Contraves/CH, Astrium/D, Alenia/I, CASA/E)*	1.55 M€
- Initial development of large deployable boom structure concepts; *(Astrium/D/F, SENER/E, Contraves/CH)*	2.05 M€
- Initial development of solar array structures (structural models, testing, complementing other studies, TRP)	1.45 M€

2006-2010	**11.0 M€**
- Further development of inflatable structure technologies (materials, folding techniques, interfaces/joints, stability, smart control etc); *(Contraves/CH, Astrium/D, Alenia/I, CASA/E)*	1.5 M€
- Development of large inflatable demonstrator for on-ground testing; *(Contraves/CH, Astrium/D, Alenia/I, CASA/E)*	1.5 M€
- Development of inflatable structure flight demonstrator *(Contraves/CH, Astrium/D, Alenia/I, CASA/E)*	3.0 M€
- Development of deployable boom structure or radiator or solar concentrator demonstrator. Configuration will be selected based on the results of the Phase-1 studies; *(SENER/E, Contraves/CH, DLR/D, Astruim/D)*	2.5 M€
- Developments for ultra-stable reflector structure technologies, design of demonstrator (complemented by additional funding from other programmes TBD); *(TU-Munchen/D, Alenia/I, CASA/E, HTS/CH, Media-Lario/I)*	2.5 M€

could be used as the support for an antenna or for a solar generator. In 2002 the work will aim at larger structures and in-flight demonstration. This work is the natural continuation of ESA's previous activities in inflatable technology, where promising results were achieved but never brought to the level of an in-flight demonstration.

In the area of a Large Deployable Antenna (LDA), many technology activities were carried out in the past at ESA and in European industry, but with no specific application. The requirements of the third-generation mobile phone applications means that LDA work is underway within ARTES-5 to produce an Engineering Qualification Model 12 m in diameter with technology capable of being extended to 25 m.

3.5 Justification and Rationale

Inflatable and deployable technologies will provide the capability to deploy very large appendages such as solar arrays/concentrators and thermal radiators for NEP, enabling missions with high power demand at remote distance from the Sun. Large antennas are also necessary for manned missions to planets where an orbiting telecommunication network would insure high data-rates from point-to-point on the surface or with Earth.

Currently mini-satellites have demonstrated that they can provide low cost missions, mainly by cutting down the launch costs. However, payloads on these small spacecraft often suffer from the limited dimensions that restrict the size of the antennas or of the solar generators. A spin-off of these technologies would be to enhance drastically the capability of small platforms by providing larger deployed solar generators or larger antennas.

3.6 Technology Roadmap

The first step, for the coming 5 years, is the in-flight demonstration of the European inflatable technology that was developed in the 1980s and that ESA intends to update within the current TRP. The activity could then be tailored to support the yet-to-be defined exploration missions, including solar arrays or a sunshield for the Next Generation Space Telescope. Other applications could arise as a function of the selected missions.

For LDAs, new concepts for higher frequencies, where better surface accuracy is required, need to be developed. In addition, these new concepts can be tailored for use as large solar concentrators.

3.7 Technology Programme Proposal

The technology programme proposal is presented in Table A10.3.

4 Materials Technologies

4.1 Introduction

In the coming years, trends will not change in materials technology for space application. The volume and mass are limited by the launcher, so the main concerns will remain volume- and mass-saving, improved use of available materials and mastering the maintenance associated with it. At least three different mission types can be defined for the next 10 years, sometimes overlapping:

— on Earth, technologies such as the space-elevator and launch-tower;
— on planets and moons, technologies combating greater temperature ranges and aggressive atmospheres;
— manned technologies with safety and autonomy as the driving parameters.

4.2 Technology Item Description

Nano-technoligies offer possibilities for many applications. For instance, a space elevator requires cables of great length and strength but of low weight. Candidates include carbon nano-tubes, which can be 100 times stronger than steel. Tethers could be developed from the same technology.

Nano-composites, ODS (Oxide Dispersion Strengthened) and nano-crystallines are potentially stronger than current materials. They can be used together with CFRP and other organic-matrix composites to build a 15 km-high launch-tower. These materials can be used for structures, as can metallic foams, and the porous Sol-Gel processed ceramics in a 3D honeycomb.

For planetary exploration, entry vehicles and reusable launchers, materials with improved temperature ranges have to be developed, covering from a few K up to about 2500°C.

Ultra-light materials, foams and felts will be increasingly needed, for insulation and solar sails. Development of in-space foaming techniques will save room aboard spacecraft and can be included in the development of inflatable structures.

Solid metallic foams are attracting the attention of the aerospace industry for their unique combinations of physical and mechanical properties such as high strength (both in tension and compression), high stiffness-to-weight ratios, excellent impact energy and sound absorption. Metallic foams can be used in combination with more traditional structural elements (typically in sandwich structures), where high stiffness and low density are required, e.g. for large deployable structures.

Several material technologies have to be developed for planetary manned exploration. Self-healing materials can improve the safety of a space station or of habitats on moons and planets. In the long-term, crews have to achieve a degree of self-sufficiency by taking advantage of the natural environment. Mining technologies, extraction and transformation from ores, silicon dioxide and iron dioxide could lower drastically the cost of such colonies. Additionally, some of these natural resources could be used for oxygen or fuel production. The natural environment could also be used for energy production, e.g. atmosphere-based (wind or stream), geothermal or even human-based. In any case, energy storage technologies would have to be developed: high-temperature superconductors or reversible chemico-physical transformations. An important effort on organic and non-organic waste treatment technology has to be made, in order to recycle as much as possible of all materials.

Discontinuously Reinforced Aluminium (DRA) is an extremely versatile class of material offering, in comparison with unreinforced aluminium alloys, an attractive balance of specific stiffness and strength, enhanced wear resistance, thermal conductivity and low thermal expansion. In DRA, the aluminium alloy matrix is reinforced by intermetallic particles or by whiskers tailoring properties in local regions. DRA can be cast or processed by powder metallurgy. It can be used in spacecraft structural and thermal management components, where high strength and stiffness, and resistance to impact and erosion are required.

Electron Beam-Physical Vapour Deposited (EB-PVD) thermal barrier coatings are protective coatings designed to increase the oxidation/corrosion resistance of the substrate alloys. This is achieved by depositing coating materials of low thermal conductivity. Using the EB-PVD process allows the coating to be deposited according to a strain-tolerant columnar microstructure. The EB-PVD coating can be deposited on highly stressed hot components to achieve thermal shock and erosion resistance superior to traditional plasma sprayed coatings. Areas of application include thermal shock-tolerant protective coating of hot structural components to increase resistance to oxidation, erosion and creep.

In addition to the above, the full set of existing materials and those still not used in space should be reviewed (including biocomposites and quasi-crystals) to assess their potential use.

4.3 Status

Considering the diversity of potential materials, the status of the technologies range from infancy to highly advanced. The most advanced technologies are the CFRP and other composites, where there are already many space applications. Scaling and improving processes are near-term goals. Other technologies are well-mastered on the ground, such as material fabrication and recycling, but adapting them to space applications and environments is a real challenge.

Among the technologies listed, some are widely developed but without any space application in mind. This is the case for clean energy production and its storage using a solid-liquid transformation. Some technologies are in their infancy even on Earth, including nano-technologies and high-temperature supra-conductors.

Studies are being carried out into solid metallic foams by the automotive and aerospace industries in order to improve fabrication processes and our understanding of the mechanical behaviour.

Several development studies on DRA sponsored by aerospace and automotive industries are in progress. The first experimental applications involve fan exit guide vanes with increased impact and erosion resistance for Pratt & Whitney turbofans, and F-16 aircraft ventral fins with fatigue-after-impact life superior to traditional aluminium alloy fins.

EB-PVD thermal barrier coatings have been recently introduced and are under development at different locations.

4.4 European Technology Programmes

Depending on the technology mentioned above, the programmes at national or international level range from insignificant to important.

4.5 Justification and Rationale

Many, if not all, subsystems of an exploration spacecraft require new material developments, some more urgently than others. For many of those described above, it is clear that other space missions, such as commercial satellites, and terrestrial projects could benefit from such developments.

4.6 Technology Roadmap (Next 30 Years)

Apart from the emergence of new materials, the main issue to be solved is the upscaling of production, either by increasing the size of individual

Table A10.4a: Technology Programme Proposal for Materials (2002-2006).

2002-2006	**4.5 M€**
- Development of alternative curing technologies (low temperature, automated e-beam) for large CFRP structures *(e.g. by EADS/F, Laben/I, Inasmet/E, Seibersdorf/A, Union-Chimique/B)*	1.4 M€
- Evaluation of processing parameters of DRA with respect to their mechanical properties for structural application *(e.g. by LKR/A, INASMET/E)*	1.0 M€
- Development of aluminium/magnesium foams contained in thin outer skin, determination of mechanical properties *(e.g. by LKR/A, Plansee/A, INASMET/E)*	1.1 M€
- Study of potential uses of nanotubes (carbon and others) in space applications *(e.g. by CSIC/E, Univ Graz/A, Univ Vienna/A, Starlab/B, Univ Leuven/B)*	0.2 M€
- Conceptual assessment of material cycle improvement (multiple recycling) for manned missions-in spacecraft or on ground *(e.g. by University of Madrid/E, INDI/E, University of Leoben/A, CERTECH/B…)*	0.2 M€
- Process Vs microstructure improvement of TBC	0.2 M€
- Assessment of uses of nano-composite and nano-crystal materials, for space applications *(e.g. by CSIC/E, Univ Graz/A, Univ Vienna/A, Starlab/B, Univ Leuven/B)*	0.2 M€
- Assessment of bio-materials (bones, sea urchin spines, wood, etc.) as models for advanced future structural materials	0.2 M€

components or developing/improving joining technologies. Most of our effort in the future should be dedicated to obtaining, at an early stage, representative samples demonstrating the validity of concepts.

4.7 Technology Programme Proposal

The technology programme proposal is presented in Table A10.4.

5 Thermal Control Technologies

5.1 Introduction

The following sections define the thermal control technologies required to support robotic or manned missions for exploration of the Solar System. The main thermal control challenge is to cope with the extreme environmental conditions encountered during such missions. The technologies are intended to:

ease/improve the transport of heat

— loop heat pipe deployable radiators
— variable thermo-optical properties coatings

Table A10.4b: Technology Programme Proposal for Materials (2006-2020).

2006-2010	**5.5 M€**
Production of demonstrator CFRP structures obtained using alternative curing technologies (low temperature, automated e-beam) *(e.g. by EADS/F, Laben/I, Inasmet/E, Seibersdorf/A, Union-Chimique/B)*	1.0 M€
- Process Vs microstructure improvement of TBC	0.3 M€
- Production of structures made of DRA *(e.g. by INASMET/E, LKR/A)*	1.0 M€
- Development of demonstrators made of aluminium/magnesium foams contained in thin outer skin *(e.g. by LKR/A, INASMET/E)*	1.0 M€
- Development at demonstrator scale of nanotube based materials (TBC)	1.5 M€
- Assessment on clean energy production on moon/planets	0.2 M€
- Development of enhanced cycle (multiple recycling) demonstrators for manned missions-in spacecraft or on ground	0.5 M€

2010-2020	**14.25 M€**
- Production of ultra-large CFRP structures using alternative curing technologies (low temperature, automated e-beam)	3.0 M€
- Process Vs microstructure improvement of TBC	2.5 M€
- Development of nano-composites and nano-crystals model materials, determination of properties, manufacturing demonstrators	2.5 M€
- Manufacturing of structural parts made of aluminium/magnesium foams development of in space foaming technologies	2.0 M€
- Development of model structures based on bio-material models	1.5 M€
- Production of nanotube-based structural parts	1.5 M€
- Demonstration of ‘self-healing materials’ concept validity, evaluation of selected model	0.5 M€
- Development of industrial transformation processes of nano-composites, nano-crystals, production of demonstrators(firm)	0.5 M€
- Conceptual assessment of transformations from ores in the different moon/planets, known materials fabrication	0.25 M€

— high heat-lift mechanical coolers
— micro-coolers for planetary landers
— high-efficiency heat pumps (270-370K)
— micro-electromechanical systems

limit heat leaks
— variable thermo-optical properties coatings
— thermal switches

store heat or cryogenic propellants
— cryogenic fuel densification (see Annex 8)
— soil heat exchangers

generate electric power from solar energy
— thermoelectric systems

5.2 Technology Item Description

High-Temperature Insulating Materials

In the presence of an atmosphere, a planetary habitat or entry vehicle needs some kind of insulating material. The idea is to develop a lightweight insulating material able to withstand high temperature levels and heat fluxes in a moderate to dense atmosphere. Since it will also be used for the space habitat, its toxicity has to be studied. In addition, the process for applying it at its destination has to be investigated.

Loop Heat Pipe Deployable Radiators

Loop heat pipes can transfer greater energy flux than standard heat pipes. Flexible, lightweight and micrometeoroid-tolerant, highly reliable deployable radiators that can be stowed for transport and deployed for use on spacecraft or planetary surfaces need to be developed.

High Heat-Lift Mechanical Coolers

High heat-lift coolers are required for zero-loss propellant storage, propulsion liquefaction, sample storage and advanced medical systems. We propose to develop large heat-lift coolers in the 80K and 10-20K ranges.

Micro-Coolers for Planetary Landers

The mass and power consumption of existing European and US coolers are too high to be used on planetary landers. On-ground coolers with low mass and power consumption are already used mainly for military applications, and could be upgraded for planetary missions. This technology could be useful for imminent interplanetary missions such as BepiColombo.

High-Efficiency Heat Pumps

Heat pumps can effectively cool a vehicle or habitat using a refrigeration cycle and reject the heat load at a higher temperature. They can be used either for satellite application or for permanent planetary bases.

Micro-ElectroMechanical Systems (MEMS)

MEMS are integrated micro devices or systems combining electrical and mechanical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from microns to millimetres. These systems can sense, control and actuate on the microscale, and function individually or in arrays to generate effects on the macroscale. The following thermal hardware can make use of MEMS technology:

- heat pipe (for local cooling of electronic components);
- tuneable thermo-optical optical coatings (smart coatings).

Variable Thermo-Optical Properties Coatings

Owing to the extreme thermal conditions encountered during Solar System exploration, smart coatings would help to absorb or dump heat as required by the thermal control system. The thermo-optical properties (solar absorptance and infrared emittance) would change under a small electrical current.

Thermal Switches
At large distances from the Sun or during planetary night, reducing thermal leaks to deep space are of prime importance. To this ed, lightweight thermal switches have to be developed.

5.3 Status

High Temperature Insulating Materials
There is no known current development in Europe.

Loop Heat Pipe Deployable Radiators
A fully qualified European deployable loop heat pipe radiator is still not available.

High Heat-Lift Mechanical Coolers
Cryocoolers with a medium heat-lift capability have been developed in Europe and are available as a commercial product from Astrium UK. Air Liquide (F) is also involved in several space projects and has delivered the Cooler for MELFI (Minus Eighty-degree Laboratory Freezer for the ISS). A great deal of development has been performed in the USA in the cooler field. As a result the second generation of pulse tube coolers are now available in the USA.

Micro-Coolers for Planetary Landers
As far as is known, micro-coolers have not been developed.

High-Efficiency Heat Pumps
Similar programmes are underway in the USA, and different classes of heat pumps are at being studied.

Micro-ElectroMechanical Systems (MEMS)
A feasibility study into miniaturising some of the identified items (heat pipe and smart coating) is imminent. However, no commercial availability for space application is foreseen before 2005-2006.

Variable Thermo-Optical Properties Coatings
Development of a similar product (ESTHER) began in Germany about 13 years ago. There has been no flight demonstration.

Thermal Switches
There are no known development programmes underway.

5.4 European Technology Programmes

High-Temperature Insulating Materials
Some insulating materials have been developed in Europe for entry probes (Huygens). However, it turned out that the raw product was toxic to humans and thermally inefficient in a dense atmosphere (2 atm).

Loop Heat Pipe Deployable Radiators
Some technology programmes have been developed in Europe, including

CNES. US and Russian telecommunication satellites are already using this technology.

High Heat-Lift Mechanical Coolers
A whole family of coolers has been developed under TRP contracts for temperatures ranging from 2.5K to 80K. The development of second-generation coolers offering low and medium heat-lift is under way.

Micro-Coolers for Planetary Landers
No technology programme has been performed in Europe.

High-Efficiency Heat Pumps
No technology programme has been performed in Europe. No programme is known of in the USA.

Micro-ElectroMechanical Systems (MEMS)
Similar concepts are under development in the USA.

Variable Thermo-Optical Properties Coatings
Activity on these coatings recently began at ESA.

Thermal Switches
Very heavy mechanical concepts have been developed.

5.5 Justification and Rationale
All of the identified thermal control technologies are needed for exploration missions, some of them for more than one mission scenario. Many of the technologies described above would benefit other space missions, including commercial spacecraft, as well as terrestrial projects.

5.6 Technology Roadmap (Next 30 Years)
The technology roadmap for the next 30 years remains to be determined.

5.7 Technology Programme Proposal
The technology programme proposal is presented in Table A10.5.

6 Conclusions

The structures, materials and thermal control technologies needed for exploration missions (manned and unmanned) have been defined. For each structural sub-group (habitat structures, lightweight structures, etc.), the status of the technology has been addressed, and new developments for the periods 2002-2006, 2006-2010 and 2011-2020 have been proposed with preliminary order-of-magnitude costs indicated (Tables A10.1-A10.5; broken down by year in Tables A10.6-A10.9). It is assumed that more detailed system/mission studies will be continued after 2005, and that required structures/materials/thermal technologies will be developed further in parallel. Therefore, only technologies that could have a major impact on the

Table A10.5: Technology Programme Proposal for Thermal Control.

2002-2006	**4.45 M€**
- Loop Heat Pipe Deployable Radiators, design	0.25 M€
- Loop Heat Pipe Deployable Radiators, design, breadboard testing development model	0.6 M€
- Micro-Coolers for Planetary Landers. Upgrade of commercial coolers pre-qualification programme	1.0 M€
- High-Efficiency Heat Pumps, design	0.3 M€
- High-Efficiency Heat Pumps, breadboard testing and qualification	0.6 M€
- Micro-ElectroMechanical Systems (MEMS): Feasibility study and design	0.3 M€
- Micro-ElectroMechanical Systems (MEMS): Breadboard testing and qualification	0.4 M€
- Thermal Switches: Feasibility study and design	0.2 M€
- Thermal Switches: Final design, breadboard testing, qualification	0.6 M€
- Variable Thermo-Optical Properties Coatings, investigation on materials	0.2 M€

2006-2010	**3.1 M€**
- Variable Thermo-Optical Properties Coatings, qualification and testing	0.3 M€
- High-Temperature Insulating Materials, Development, manufacturing and testing	0.6 M€
- High Heat-Lift Mechanical Coolers, design, breadboard testing, EQM design and pre-qualification testing	2.2 M€

feasibility of the to-be-selected mission concepts are proposed to be addressed during the 2002-2006 period. Other important but less critical technologies, as well as the detailed development of critical technologies, will thus have to be performed after 2005.

All of the addressed technologies are essential for exploration missions, but in most cases not only for such missions. This means that funding from other sources will and should be explored in parallel, such as FLTP/RLV, TRP, ASTE and ARTES. It also means that the developed technologies are needed for other ESA programmes independent of the exploration programme schedule.

Table A10.6: Technology Programme Proposal Summary for Habitat Systems (in € million).

Activity	2002	2003	2004	2005-2006	Total Phase-1	2006-2010	2010-2020
Habitat Structural Systems							
Preliminary configuration studies, structural concepts			0.1	0.2	0.3	0.5	
Development of numerical tools, repair aspects, NDI (numerical tools in Phase-1 only)			0.1	0.2	0.3	5	10
Initial development of on-orbit welding techniques				0.5	0.5	1.5	
Development of in-orbit welding demonstration hardware						2	
Development of larger (sub-scale) habitat demonstrator structures							2
Preparation of in orbit welding demonstration							tbd
SUM			0.2	0.9	1.1	9.0	12
Habitat Related Technologies							
Evaluation of high-speed impact test facilities		0.1	0.1		0.2		
Development of numerical tools for simulation of high-speed M/D impact	0.1	0.1	0.1	0.2	0.5		
Initial development of lightweight shields for habitat systems						0.5	
Initial development of health monitoring concepts for manned systems		0.1	0.1	0.3	0.5	0.6	
Initial development of NDI methods		0.1	0.1	0.4	0.6	0.6	
Initial development of repair methods				0.5	0.5		
Detailed shielding concept development for selected missions							1
Development of NDI demonstrator facility						2	
Develoment of health monitoring system for selected missions						1	
SUM	0.1	0.4	0.4	1.4	2.3	4.7	1

Table A10.7: Technology Programme Proposal Summary for Large Lightweight Inflatable and Deployable Structure (in € million).

Activity	2002	2003	2004	2005-2006	Total Phase-1	2006-2010	2010-2020
Further development of inflatable structures technologies, folding techniques, interfaces/ joints,materials, stability, smart control etc	0.1	0.3	0.40	0.75	1.55	1.50	
Development of large inflatable demonstrator (Solar Array/Shield/reflector/..) for on-ground testing						1.5	
Initial development of large deployable boom structure concepts	0.1	0.25	0.20	1.5	2.05		
Initial development of solar array structures, structures models, testing, complementing other studies	0.1	0.15	0.20	1.0	1.45		
Development of inflatable structure flight demonstrator						3.0	
Development of deployable boom structure or radiator or concentrator demonstrator. Configuration will be selected based on the results of the phase-1 studies						2.5	
Developments for ultra stable reflector structures technologies and design of demonstrator						2.5	
SUM	0.3	0.7	0.8	3.25	5.05	11	TBD

Table A10.8: Technology Programme Proposal Summary for Material Technologies (in € million).

Activity	2002	2003	2004	2005-2006	Total Phase-1	2006-2010	2010-2020
Development of alternative curing technologies, (low temperature, automated E-beam) for large CFRP structures	0.1	0.25	0.3	0.75	1.4		
Evaluation of processing parameters of DRA wrt their mechanical properties for structural applications	0.1	0.15	0.25	0.5	1.0		
Development of Aluminium/Magnesium foams	0.1	0.25	0.25	0.5	1.1		
Study of the potential use of nanotubes (carbon and others) in space		0.1	0.1		0.2		
Conceptual Assessment of material cycle improvement (multiple recycling) for manned missions				0.2	0.2		
Production of demonstrator structures using alternative curing technologies						1	
Process versus microstructure improvement of TBC				0.2	0.2	0.3	
Production of structures made of DRA						1	
Assessment of uses of nano-composites and nano-crystal materials for space application				0.2	0.2		
Development of demonstrators made of aluminium/magnesium foams						1	
Assessment of Bio-Materials (bones, sea urchin spines, wood etc) as models for advanced future structural materials				0.2	0.2		
Development at demonstrator scale of nanotube based materials						1.5	
Assessment on clean energy production on Moon/planets						0.2	
Development of enhanced (multiple recycling) demonstrators for manned missions, (in spacecarft or on surface)						0.5	
Production of ultra large CFRP structures using alternative curing technologies							3
Process versus microstructure improvement of TBC							2.5
Development of nano-composites and nano-crystal model materials, determination of properties, manufacturing of demonstrators							2.5
Manufacturing of structural parts made of aluminium/magnesium foams							2
Development of model structures based on Bio-materials models							1.5
Production of nano-tubes based parts							1.5
Demonstration of self-healing materials, concept validity. Evaluation of selected model							0.5
Development of industrial transformation processes of nano-composites, production of demonstrators							0.5
Conceptual assessment of transformations from ores…							0.25
SUM	0.3	0.75	0.9	2.55	4.5	5.5	14.25

Table A10.9: Technology Programme Proposal Summary for Thermal Control Technologies (in € million).

Activity	2002	2003	2004	2005-2006	Total Phase-1	2006-2010	2010-2020
Loop Heat Pipe Deployable Radiators, design		0.1	0.15		0.25		
Loop Heat Pipe Deployable Radiators, design, breadboard testing, development model				0.6	0.6		
Micro-coolers for planetary landers	0.1	0.1	0.2	0.6	1.0		
High-Efficiency Heat Pumps, design		0.1	0.2		0.3		
High-Efficiency Heat Pumps, breadboard testing and qualification				0.6	0.6		
Micro-Electro Mechanical Systems feasibility study and design	0.1	0.1	0.1		0.3		
Micro-Electro Mechanical Systems, breadboard testing and qualification				0.4	0.4		
Thermal Switches, feasibility study and design			0.1	0.1	0.2		
Thermal Switches, final design, breadboard testing, qualification				0.6	0.6		
Variable Thermo-Optical Properties Coatings, investigations on materials		0.1	0.1		0.2		
Variable Thermo-Optical Properties Coatings, qualification and testing						0.3	
High Temperature Insulating Materials, development, manufacturing and testing						0.6	
High Heat-Lift Mechanical Coolers, design, bread-board testing, EQM design and pre-qualification						2.2	
SUM	0.2	0.5	0.85	2.9	4.45	3.1	tbd