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HUMAN SPACEFLIGHT: ACHIEVEMENTS, BENEFITS AND FUTURE OPPORTUNITIES FROM A EUROPEAN PERSPECTIVE

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Abstract. The past achievements, benefits and future opportunities of human spaceflight are discussed from a European perspective. Earlier work performed on the Skylab, Salyut, Shuttle, Spacelab, and Mir orbital facilities is reviewed, together with the prospects for new research on the International Space Station (ISS). Major scientific benefits are expected from the ISS in the areas of life science research (including human physiology and medicine) physical sciences, and fundamental physics.

Keywords: International Space Station, space life sciences, space physical sciences, microgravity, space medicine, space exploration

1. Historical Background

1.1. Introduction

The space age began almost 50 years ago, when the former Soviet Union and the United States, at the peak of the cold war, made tremendous efforts in meeting the challenges of sending the first satellite and the first human being into low Earth orbit. The first extraordinary spaceflights were achieved by the Soviet Union on 4 October 1957 with the launch of the first artificial satellite, Sputnik 1, and 3.5 years later with the flight of Yuri Gagarin in an Earth orbit on 12 April 1961. The launch of Sputnik shocked the USA out of its complacency regarding its technical superiority, and, during the rush to recover the initiative, NASA was formed in 1958. In 1960, announcing NASA's Apollo Programme, President Kennedy made the famous statement that it was an American national objective to land an American on the Moon before 1970, and in July 1969 the world witnessed one of the most spectacular technical achievements in the history of mankind when this was achieved. With the successful accomplishment of this objective, the USA demonstrated their superiority in high technology and confirmed their lead in the space race with the Soviet Union.

Since the mission of Yuri Gagarin more than 400 people from many nations have experienced the wonders of seeing our blue planet from space. Although human exploration and exploitation of space during the second half of the 20th century was dominated by the former Soviet Union and the United States, with Europe, Japan and Canada cooperating on various programmes, notably the International Space Station (ISS), this fairly exclusive club has – in October 2003 – been joined by China the third nation to launch its first "Taikonaut" into orbit.

1.2. The origin of research associated with human spaceflight

During the 1970's, the USA and the Soviet Union alone had access to the environment that exists in a freely drifting spacecraft, or in an orbiting satellite. Characterised by it's weightless or free-fall conditions, with the gravitational and inertial forces in balance over an extended period, this "microgravity" environment cannot be produced on Earth for lengthy periods of time. To achieve it, it is necessary to go into space. The term microgravity itself reflects the reality that true weightlessness, or zero gravity, is a condition that cannot be achieved in practical systems as the acceleration of the spacecraft when thrusters are fired, or the friction of a spacecraft with the residual atmosphere, induces gravitational effects.

Early microgravity experiments made use of a variety of orbiting spacecraft, mostly manned and with the crew being used as test subjects in human physiology studies. Following initial testing with animals, the early human space flights confirmed that there was no immediate danger to life posed by weightlessness. However, a large number of effects on the function of heart, lungs, bones, and muscles and nervous system were detected during early human spaceflight missions, which required detailed investigation because they were seen as potential risks to astronauts on long-duration spaceflight. Most research was initially focused on human physiology, and was directed towards macroscopic effects on the body. Later the research was extended to explore changes at microscopic level i.e. broadening the research into gravitational biology, exobiology and radiation biology. This meant that studies were performed in space on functional changes of cells, tissue, plants, animals and humans, under conditions in which the effects of gravity are removed. This condition is different from that on Earth, where life has evolved during the last 3.5 billion years with the permanently present influence of the force of gravity.

In addition to research in life sciences, there has also been a considerable programme of research in fluid- and materials sciences, which is of significant scientific interest, having the potential for improving industrial processes. Changes in the behaviour of fluids in space lie at the heart of this research as under microgravity conditions, the basic gravity-induced phenomena of sedimentation, buoyancy and convection flows and hydrostatic pressure, are practically absent. By removing gravity-induced effects, experimental conditions can be greatly simplified and the fundamental processes in fluids can be more readily explored. Controlling the behaviour of fluids, particularly regarding heat and mass flow, facilitates a better understanding of, and subsequently improvements to, a whole range of industrial processes that depend upon fluids. For example, knowledge gained in space has applications in metal casting and crystal growth which on Earth is constrained by the turbulent conditions induced by gravity. Other early research topics included the study of factors controlling defect generation during growth from the melt of commercially important materials such as semi-conductors.

Since the early US and Soviet spacecraft were not designed as laboratories for life and physical sciences studies, there was insufficient space to accommodate sophisticated research equipment. This led to the creation, in the 1970's, of the American Skylab programme and the Soviet Salyut orbital stations.

1.3. The Skylab and Salyut orbital stations

Skylab was a derivative of the third stage of a Saturn-5 rocket, modified to act as an orbital laboratory. It was large enough (15 m in length, 6.6 m in diameter) to accommodate three astronauts, life-support equipment, and research equipment for life and physical sciences, as well as several astronomy and Earth observation instruments. This 99 ton orbital station was launched into a 400 km, 50 degree inclination, orbit in May 1973, and was visited by three crews of three astronauts for periods of 28, 60 and 84 days in 1973/early 1974. Skylab remained in orbit, unmanned and with no remote experimental use for a further 5 years after which, in 1979, NASA executed a controlled re-entry into the atmosphere.

During these three pioneering Skylab missions, very valuable experiments in life and physical sciences were carried out, which attracted worldwide interest in many research fields. It was demonstrated that this type of research would lead to advances in fundamental understanding of materials properties and to discoveries of new life sciences phenomena.

However, a full appraisal of the potential of space life and physical sciences was not possible after these three Skylab missions, because the Skylab experiments were hastily prepared and the furnaces, crystallisation chambers, biomedical instruments, etc, were rudimentary when compared with the high performance facilities developed later (e.g. for Spacelab, see below), and many potential research areas in life and physical sciences were not addressed on Skylab at all.

The Soviet Union took its first steps in the direction of a space station in April 1971 with the launch of the Salyut-1 orbital station, which comprised of a cylindrical module, 13 m long and 3.6 m in diameter. Several improved Salyut versions were subsequently launched until 1982. Salyut was visited by 10 different crews using the Soyuz transfer vehicle, the final visit lasting 100 days. The research results from these missions were not communicated or published by the Soviets, and it was only after the dissolution of the Soviet Union that it became known that a large number of space medical investigations and materials research had been carried out on Salyut and that a lot of optical equipment had been operated on Salyut for military purposes.

1.4. Spacelab and its european utilisation

Although in the 1960s Western Europe had already begun the process of combining its economic forces, and was the world's second largest economic power, Europe played no role in demonstrating technical leadership in space activities. However, the success of the Apollo programme had created a desire in Europe to participate in the next step of human exploration of space. Following the NASA announcement in 1972 of the Space Transportation System (STS) programme, which involved the development of the Space Shuttle as the major element, ESA's Member States decided, in 1973, to develop and contribute SPACELAB as an element of STS, to be built by European industry. This decision was part of a larger package of decisions that included the decision to develop the Ariane launcher system and a series of communication satellites. Spacelab became the first multi-national, multi-disciplinary research laboratory routinely used in space by American and European scientists for scientific and application oriented research activities. It proved to be ideally suited for microgravity disciplines, but less so for disciplines which required specific orbital and attitude requirements and very high data rates.

Three modules of Spacelab were available to fly in the cargo bay of a Space Shuttle. The Long Module (LM) version, which performed sixteen 7–17 day missions during the period 1983–1998, consisted of a 6.5 m long cylinder-shaped laboratory with a diameter of 4.3 m, and of up to three external pallets (2.9 m × 4.3 m) that were also accommodated in the Shuttle cargo bay. With the short module (SM) version of Spacelab, it was possible to accommodate up to five external pallets in the Shuttle cargo bay, and the pallet-only version, which consisted of five separately accommodated external pallets, could carry 9300 kg of external payloads. Seven missions with the SM or pallet-only configuration were flown. In this period, Spacelab was the workhorse for life and physical sciences for the Western World. Under the NASA/ESA Spacelab utilisation cooperation agreements European industry developed about a dozen ESA-funded multi-user life and physical science experimental facilities for joint European/American use; NASA contributed the flight and operations costs of Spacelab and these experimental facilities. With this favourable arrangement for ESA, and European scientists, these facilities flew on five NASA Shuttle/Spacelab missions and on the German D-1 and D-2 Spacelab missions in the period 1985–1998.

Unfortunately, in a period when microgravity research was beginning to take-off, the tragic accident with the Shuttle *Challenger* occurred (28 January 1986), leading to a 5-year interruption of Spacelab missions. With the Spacelab grounded, attention focused on alternative means of accessing microgravity conditions. Various types of sounding rockets (SR) were used, providing between 2 and 13 minutes of very good microgravity levels, and carrying payloads of up to 450 kg some 800 km in vertical parabolic trajectories above the Earth's atmosphere. These SR short duration flight opportunities have been maintained as precursor flight opportunities for microgravity experiments through to today, however at a lower flight frequency. Other alternative low-gravity flight opportunities, such as parabolic airplane flights (25 seconds, however only 0.01 g), drop towers (up to 9.5 seconds, good microgravity levels) and the flight of retrievable capsules, such as Bion/Foton launched by Soyuz rockets (1 week flight duration, microgravity levels as on Shuttle/Spacelab) have also been used.

1.5. The Mir Space Station and its European Utilisation

Mir, the first true, permanently orbiting space station, was assembled during the period 1986–1996 and became international in it's utilisation, although it was owned and operated by the Russian Space Agency (RSA). Consisting of a Core Module and five cylindrical research modules, each some 12–13 m in length and 4.15 m in diameter, Mir's research capabilities were somewhat constrained due to its limited data handling capabilities and by its very low payload return capabilities (only a few kg of samples could be returned to Earth in Soyuz re-entry capsules, together with crew members). This situation changed with the entry into force of a NASA/RSA cooperation agreement in 1996, which led to regular visits of the Shuttle to Mir. During its lifetime, Mir was used for experimental purposes and various European space agencies, such as CNES, DLR, ASSA (Austria), and NASA, used Mir on a commercial basis. ESA also used Mir on a commercial basis in 1994

(EUROMIR-94, a 31 days mission) and in 1995 (EUROMIR-95, a 179 days mission) with its own experimental facilities and astronauts. Utilisation ceased in 1999, and in 2001 Mir was destroyed in a controlled re-entry into the Earth's atmosphere.

Figure 1 shows the major historical milestones of Human Spaceflight. Table I lists all European astronauts flown so far, and Table II lists the number of European life and physical sciences experiments performed in the period 1971–2004.

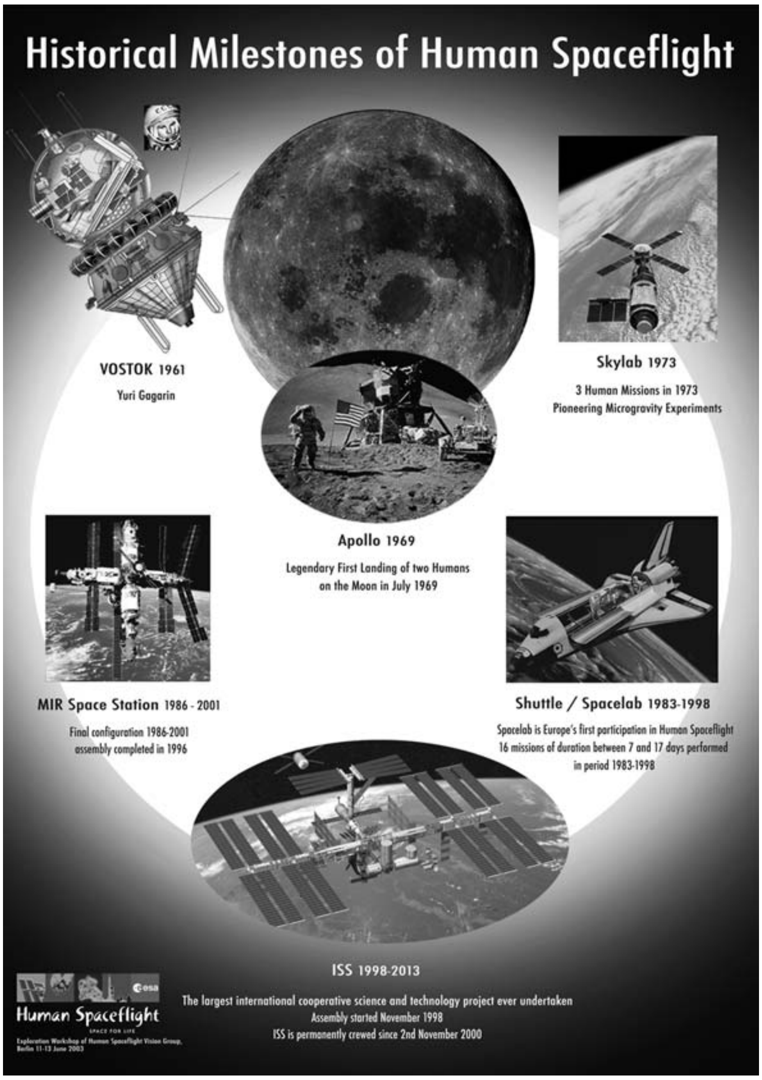

Figure 1. Some historical milestones in human spaceflight.

TABLE I
European astronauts in space

Ass.	Name	Organisation	Mission Programme/ Payload	Space Vehicle(s)	Year
1	(1) S. Jähn (D)	IKF (former GDR)	Interkosmos	Soyuz-31/Salyut-6/ Soyuz-29	26 Aug.–03 Sep. 1978
2	(2) J.-L. Chrétien (F)	CNES	Premier Vol Habité	Soyuz T-6/Salyut-7	24 Jun.–02 Jul. 1982
3	(3) U. Merbold (D)	ESA	Spacelab 1	STS-9	28 Nov.–08 Dec. 1983
4	(4) P. Baudry (F)	CNES	Spartan-1	STS-51 G	17 Jun.–24 Jun. 1985
5	(5) R. Furrer (D)	DFVLR	Spacelab D-1	STS-61 A	30 Oct.–06 Nov. 1985
6	(6) E. Messerschmid (D)	DFVLR			
7	(7) W. Ockels (NL)	ESA			
8	(2) J.-L. Chrétien (F)	CNES	Aragatz	Soyuz TM-7/MIR/ Soyuz TM-6	26 Nov.–21 Dec. 1988
9	(8) H. Sharman (GB)	Private Funding	Juno	Soyuz TM-12 /MIR/ Soyuz TM-11	18 May–26 May 1991
10	(9) F. Viehböck (A)	Austrian Space Agency	Austromir	Soyuz TM-13/MIR/ Soyuz TM-12	02 Oct.–10 Oct. 1991
11	(3) U. Merbold (D)	ESA	Spacelab Mission IML-1	STS-42	22 Jan.–30 Jan. 1992
12	(10) K.-D. Flade (D)	DARA / DLR	MIR'92	Soyuz TM-14/MIR/ Soyuz TM-13	17 Mar.–25 Mar. 1992
13	(11) D. Frimout (B)	Belgium	ATLAS-1	STS-45	24 Mar.–02 Apr. 1992
14	(12) M. Tognini (F)	CNES	Antares	Soyuz TM-15/MIR/ Soyuz TM-14	27 Jul.–10 Aug. 1992
15	(13) F. Malerba (I)	ASI	EURECA-1, Tethered Satellite System	STS-46	31 Jul.–08 Aug. 1992

TABLE I (Continued)

Ass.	Name	Organisation	Mission Programme/ Payload	Space Vehicle(s)	Year
16	(14) C. Nicollier (CH)	ESA			
17	(15) H. Schlegel (D)	DARA/DLR	Spacelab D-2	STS-55	26 Apr.–06 May 1993
18	(16) U. Walter (D)				
19	(17) J.-P. Haigneré (F)	CNES	Altaïr	Soyuz TM-17 /MIR/ Soyuz TM-16	01 Jul.–22 Jul. 1993
20	(14) C. Nicollier (CH)	ESA	Hubble Telescope 1st Servicing	STS-61	02 Dec.–13 Dec. 1993
21	(3) U. Merbold (D)	ESA	EUROMIR 94	Soyuz TM-20/MIR/ Soyuz TM-19	03 Oct.–04 Nov. 1994
22	(18) J.-F. Clervoy (F)	ESA	ATLAS-3; CRISTA SPAS 1	STS-66	03 Nov.–14 Nov. 1994
23	(19) T. Reiter (D)	ESA	EUROMIR 95	Soyuz TM-22/MIR	03 Sep. '95–29 Feb. 1996
24	(14) C. Nicollier (CH)	ESA	Tethered Satellite System-1	STS-75	22 Feb.–09 Mar. 1996
25	(20) M. Cheli (I)		Reflight USMP-3		
26	(21) U. Guidoni (I)	ASI			
27	(22) J.-J. Favier (F)	CNES	Spacelab LMS-1	STS-78	20 Jun.–07 Jul. 1996
28	(23) C. André-Deshays (F)	CNES	Cassiopée	Soyuz TM-24 /MIR/ Soyuz TM-23	17 Aug.–02 Sep. 1996
29	(24) R. Ewald (D)	DARA / DLR	MIR'97	Soyuz TM-25/MIR/ Soyuz TM-24	10 Feb.–02 Mar. 1997
30	(18) J.-F. Clervoy (F)	ESA	6th Shuttle flight to MIR	STS-84	15 May–24 May 1997
31	(2) J.-L. Chrétien (F)	CNES	7th Shuttle flight to MIR	STS-86	25 Sep.–06 Oct. 1997
32	(25) L. Eyharts (F)	CNES	Pégase	Soyuz TM-27/MIR/ Soyuz TM-26	29 Jan.–19 Feb. 1998

33	(26) P. Duque (E)	ESA	SpaceHab	STS-95	29 Oct.–07 Nov. 1998
34	(17) J.-P. Haigneré (F)	CNES, ESA	Perseus	Soyuz TM-29/MIR	20 Feb.–28 Aug. 1999
35	(12) M. Tognini (F)	CNES	Chandra X-Ray Observatory	STS-93	22 Jul.–27 Jul. 1999
36	(14) C. Nicollier (CH)	ESA	Hubble 3rd Servicing	STS-103	19 Dec.–27 Dec. 1999
37	(18) J.-F. Clervoy (F)				
38	(27) G. Thiele (D)	DLR, ESA	Shuttle Radar: Mission	STS-99	11 Feb.–22 Feb. 2000
39	(21) U. Guidoni (I)	ESA	9th ISS flight (6A) MPLM	STS-100	19 Apr.–01 May 2001
40	(23) C. Haigneré (F)	CNES, ESA	Andromède – ISS flight	Soyuz TM-33/Soyuz TM-32	21 Oct.–31 Oct. 2001
41	(28) R. Vittori (I)	ASI, ESA	Marco Polo	Soyuz TM-34/Soyuz TM-33	25 Apr.–05 May 2002
42	(29) P. Perrin (F)	CNES	ISS assy flight UF-2	STS-111	05 Jun.–19 Jun. 2002
43	(30) F. De Winne (B)	Belgium, ESA	Odissea	Soyuz TMA-1/Soyuz TM-34	30 Oct.–10 Nov. 2002
44	(26) P. Duque (E)	Spain, ESA	Cervantes	Soyuz TMA-3/Soyuz TMA-2	18 Oct.–28 Oct.2003
45	(31) A. Kuipers (NL)	Netherlands, ESA	Delta; back-up: G. Thiele (D)	Soyuz 8/Soyuz 7	19 Apr.–30 Apr. 2004
Mission assignments					
46	(28) R. Vittori (I)	ASI, ESA	ENEIDE	Soyuz 10/Soyuz 9	April 2005
47	(19) T. Reiter (D)	ESA	ESM 1 back-up L. Eyharts	Soyuz 11S/STS116	2005
48	(32) C. Fuglesang (S)	ESA	12-A.1	STS-116	NET Feb2006
49	tbd	ESA	2nd MPLM	STS tbd	2006
50	tbd	ESA	Increment E1; back-up: tbd	STS-123	2007
51	tbd	ESA	1E, Columbus delivery mission	STS-123	2007
52	tbd	ESA	2nd Early utilisation flight	STS tbd	2007

TABLE II
Number of european experiments on human spaceflight missions and precursor flights

Year	System								Yearly Total
	Sounding rockets	Parabolic flights	Apollo/ Skylab	Shuttle/ Spacelab	Retrievable capsule	Salyut	Euromir/ MIR	ISS	
Experiments performed									
1971			1						1
1972			3						3
1973			1						1
1974									
1975	1		3		1				5
1976	1								1
1977	11				1				12
1978	10					2			12
1979					1	3			4
1980									
1981	19								19
1982	19			1		6			26
1983	17			46	3	1			67
1984	17	1		6		1			25
1985	13			74	2				89
1986	8	2							10
1987	16	11			4				31
1988	34	6					13		53
1989	27	5			8				40
1990	24	14							38

1991	6	9		5	1		15		36
1992	22	3		31	25		27		108
1993	13	10		78			13		114
1994	11	10		43	7		25		96
1995	3	1		14	6		26		50
1996	2	4		32					38
1997		3		14	13		1		31
1998	8			18					26
1999	4	1			11		3		19
2000	4	7		1					12
2001	5	3						11	19
2002	7	22			29			27	85
2003	6	23						19	48
2004	5	68						21	94
Cumulative Total	313	203	8	363	112	13	123	78	1213

2. The ISS and its European Utilisation

2.1. ISS features

The ISS is the biggest orbital platform ever built, and the largest international technical project in the history of mankind. Upon the invitation of then-President Reagan, 10 European countries, represented through ESA, cooperate with the United States, Russia, Japan and Canada in the development of ISS, which since 1998 has been in its assembly phase. Following the Shuttle *Columbia* accident in February 2003 this assembly has been interrupted, but it will be resumed in summer 2005 with the Shuttle return to flight. At present the ISS is operated by a two-astronaut crew with a reduced level of support for research purposes. Astronaut and logistic transport is presently performed by Russian Soyuz and Progress vehicles.

At completion the Station will have a total mass of over 400 tons and dimensions of about 100 m $\times$ 75 m. Out of a total electrical power of 110 kW some 47 kW will be available for research purposes and it will be permanently manned by up to 6 astronauts. From a research point of view, the most important elements of the ISS are its five laboratories and the external experimental platforms. The US Laboratory "DESTINY" is already in use, but in 2004 NASA decided to delete some of its originally planned ISS elements (in particular the US Habitation Module and a new ISS Crew Return Vehicle). The laboratories of the other Space Station Partners are currently awaiting launch; these are:

- The European "Columbus" Laboratory with its External Payload Facility, whose launch is currently planned in October 2006
- The Japanese Pressurised Experiment Module "JEM" with the Exposed Facility and Robotic Manipulator System (RMS)
- The Russian Research Module (RM), which is presently in its development phase
- The Russian Multipurpose Laboratory Module (MLM), which is also in its development phase

The Canadian contribution to ISS, the ISS Remote Manipulator (consisting of a Mobile Remote Servicer Base System, Mobile Transporter, Mobile Servicing System and the Canadarm) is already onboard the ISS.

The most important elements of the European contribution to the ISS are:

(1) The multidisciplinary research laboratory, Columbus. This a pressurised module, 6.7 m long and 4.5 m in diameter with a total mass of 15 tons, five of which are comprised of research equipment. It is equipped with

both internal and external multi-user research facilities and offers a highly flexible research facility in space, in which user experiments may be carried out with the assistance of astronauts who can live and work in a shirtsleeve environment. Inside Columbus, there will be ten exchangeable payload racks (four along each side and two at the ceiling). Almost all of the experimental equipment within the pressurised module will be dedicated to life and physical sciences. At launch, Columbus will be equipped with the following ESA multi-user facilities: BIOLAB, Fluid Science Lab (FSL), European Physiology Modules (EPM) and the European Drawer Rack (EDR). On the outside of Columbus there is an External Payload Facility (CEPF) which has four locations for the accommodation of external payloads for space science, Earth observation, and fundamental physics and technology payloads (see below). The two external ESA payloads, European Technology Exposure Facility (EuTEF) and the SOLAR observatory, will be launched with the same Shuttle flight in 2007 as Columbus, but will be carried separately and accommodated in orbit on the CEPF.In addition to the experimental facilities and instruments accommodated in Columbus, ESA has developed a Materials Science Lab (MSL), a European Modular Cultivation System (EMCS), a Pulmonary Function System (PFS), and a few other life science instruments such as a Muscle Atrophy Research and Exercise System (MARES), a Percutaneous Electrical Muscle Stimulator (PEMS), and a Hand-Grip Dynamometer (HGD). Based on a special ESA/NASA agreement these ESA facilities will be, or are already, accommodated and jointly used in the US Destiny laboratory.

(2) The Automated Transfer Vehicle (ATV). This is an ISS supply vehicle whose purpose is to deliver payloads, propellants, crew supplies and various commodities, as well as to periodically re-boost the ISS to its nominal orbital altitude from which it is dragged down due to friction with the residual atmosphere.

(3) Other European contributions to ISS include:

- The European Robotic Arm (ERA), which is to be attached to the Russian segment of ISS in 2007
- Nodes 2 and 3 of the ISS infrastructure, which are to be launched in September 2006 and May 2008
- The Data Management System (DMS-R) for the Russian Segment of ISS, which was launched in 2000 as a core part of Russia's Zvezda module
- The Cupola, a truncated hexagonal pyramid (the closest shape to a spherical dome) with flat windows. The Cupola will provide external views for controlling the robotic operations of the ISS Remote

Manipulator and allow monitoring of crew space walks. It will also permit scientific and crew observation of Earth and celestial bodies
- The Microgravity Science Glovebox (MSG), a multi-purpose, multi-user experimental support facility, which is accommodated, and in use, in the US Lab since June 2002
- A minus 80°C freezer (MELFI), of which ESA has already delivered four flight units to NASA and JAXA (the Japanese Space Agency)
- Hexapod, a pointing platform for external payloads
- A refrigeration system (Cryosystem), for which launch is planned no earlier than 2008

2.2. European utilisation of ISS

The space environment of an orbiting platform, which includes as major physical feature the absence of gravity, makes the ISS a unique large extraterrestrial laboratory. The ISS is ideally suited for research in life and physical sciences, which create knowledge of great importance for terrestrial applications. In addition, the attitude and orbit of the ISS are well-suited for a variety of space science and Earth observation investigations. The Utilisation Plan of ISS foresees regular access to and from the Station, allowing for iterative research in short time scales. The laboratories of the ISS, with their numerous research facilities and instruments, offer the following opportunities for basic and applied research:

- Materials Science, including solidification physics, crystal growth and fluid physics
- Fundamental physics, including cold-atom and quantum physics, complex plasmas, and the physics of dust particles
- Life sciences, including human physiology, space medicine, space biology, radiation biology and biotechnology
- Space science and Earth observation on external platforms, which point both to deep space and towards the Earth

Furthermore, the ISS is ideally suited for technology demonstrations, by housing and testing new technologies and products in the space environment. Additionally, the ISS may be used as an education platform because of the various scientific activities performed, its high public visibility, and the presence of astronauts who can act as teachers from space.

The "European Utilisation Plan for the International Space Station" (ESA document SP-1270) provides details on ESA's ISS research plan. Based on several Announcements of Research Opportunities (AO's) ESA has selected, with the help of international peer review groups, 252 Basic Research proposals, and 45 Microgravity Application Projects (MAP's), for the ISS.

The MAP Programme was launched by ESA about 10 years ago to involve non-space industry in joint projects with scientists from universities/ research institutes. Today there are 45 European MAP's, which are typically financed one-third by industry, one-third by ESA, and one-third by universities and research institutes which normally provide the Principal Investigators. Of the 45 MAPs, 26 are from life sciences and 19 from physical sciences; 145 companies participate actively in these MAPs, and more than 1000 European scientists are involved in the selected research projects.

3. Achievements, Benefits and Future of Human Spaceflight

3.1. Life science

3.1.1. *Space biology, radiation biology and biotechnology*

The main objective of space biology is to study the effects of gravity and radiation on cells, tissues and whole-body development and reproduction. The results of space experiments have shown altered gene expression and signal transduction, changes in membrane composition and functioning, as well as changes to energy metabolism and cell proliferation. Chromosomal abnormalities have also been detected, as well as disturbances in the partitioning of genetic material in some experiments on plants cells. By the use of centrifuges in space variable gravity levels can be applied, and ESA's Biorack experiment, which has flown six times, had variable 0 to 1 g centrifuges to investigate gravity sensitivity and thresholds for these effects. These Biorack experiments demonstrated that certain cell activities were already reduced or even inhibited at 0.3 g, but that the metabolic functions of osteoblast cells are fully recovered by 1 g centrifugation in space. This is very important for manned missions to Mars, where the gravity level is 0.38 g; this result is also important for studies on osteoporosis and its cure or prevention on Earth. At the tissue level, altered cell–cell relations have been observed in stable and controlled fluidic systems in space.

The successor of the Spacelab Biorack facility, the ISS facility Biolab, also includes variable g centrifuges, which will be used for 1 g reference experiments and threshold measurements on various cell types, plants and other organisms. Studies are planned on the ISS to clarify how far subtle gravity-induced modifications are due to different mechanical and biochemical micro-environments. Specifically, on the ISS it is planned to address and understand:

- Mechanisms of cell proliferation and differentiation
- Effects of mechanical loading
- Role of the cytoskeleton on signal transduction
- Graviperception and g-level threshold detection

With respect to future long-term human space missions to Moon and Mars it is of utmost importance to develop, not only adequate countermeasures to reduce the effects of low gravity, but also to perform research into the effects of space radiation on the human body. In order to obtain precise radiation data, the German Aerospace Centre DLR, together with ESA, have developed the radiation biology payload Matroshka. This is a body radiation-dosage measurement unit, which was mounted externally on the Russian Service Module of the ISS in February 2004. It is a tissue-equivalent phantom representing the upper part of the human torso, and is composed of natural bone and of various tissue substitutes simulating the human body as far as size, shape, orientation, mass density and nuclear interactions are concerned. At the sites of the body organ locations, such as stomach, lungs, colon, eyes and skin, spaces are provided at the surface and at different depths within the phantom to accommodate dosimeter packages to measure ionising radiation. Knowledge of the radiation dosage to which sensitive organs of astronauts are exposed is very important for evaluating the risks from radiation on the ISS, especially during extra-vehicular activities, and for future long-duration space missions. The data gathered will be used to reduce uncertainties in risk estimates for radiation-induced cancer, and for the refinement of the shielding needs for vehicles used for future long-duration missions. They also have important implications for ISS crew health and mission planning.

Biotechnology ranges from genetic enhancement of agricultural plants, to the understanding of the impact of the micro-environment on cells and tissues for bio-organ and tissue engineering. In the domain of Biotechnology on the ISS it is planned to investigate the influence of microgravity on trans-membrane and intracellular flux mediators controlling differentiation, cell-matrix interaction and cell potency. Studies in space are needed to determine the influence of gravity on the processing and amplification of signals in cells, cell aggregation, tissue and whole organisms. Advancements of these fundamental aspects are important for transplantation of tissue and organs, and for the growth of tissue samples outside the body (e.g. for the replacement of human organs and tissue by *in vitro* grown tissue material and organs). Cell and organ cultures open up new ways to prevent and to treat diseases, and previous bioreactor experiments in space have shown improved growth of 3-dimensional tissues. On the ISS it is planned to grow skin and liver tissues, and even cancer tumours, with the prospect of applications for transplantation of artificial tissue and organ-like structures and the production of pharmaceutical agents. Plant tissue culturing experiments using bioreactors in space may also have applications in agriculture. About 50 European companies cooperate with research institutes in ESA-selected Microgravity Application Projects in the field of biotechnology and biomedical applications (see ESA BR-141).

3.1.2. *Human physiology and space medicine*

(a) *Cardiovascular System Changes in Space:* Among the first changes observed in astronauts was a de-conditioning of the cardiovascular system, similar to that developing in the normal ageing process on Earth. An upward displacement of up to two litres of body fluid, when entering weightlessness, was followed by an increased fluid and electrolyte excretion by the kidneys, increased pumping of the heart, and a redistribution and reduction in blood plasma. In addition there is an apparent depression of the immune system's response to infection.

Research in space of these processes constitutes a valuable tool to extend the understanding of blood pressure mechanisms, blood constituents, and of basic body fluid regulation involving heart, kidneys and the glandular system. The investigation of aging symptoms and de-conditioning arising in space in young healthy astronauts allows the development and testing of counter-measures, using subjects free from other complicating characteristics.

(b) *Respiratory System Changes in Space:* Changes in the chest-wall mechanics, and relative displacement of the rib cage and the abdominal compartments, have been detected as the consequence of entering into the microgravity of space. The details of lung ventilation and blood perfusion patterns in weightlessness will be the subject of research projects on astronauts on the ISS.

(c) *Bone Mass Loss in Space:* To understand the detected acute bone mass loss of about 1% per month in load carrying bones of astronauts, research projects have been started to study processes at cellular, tissue, molecular and hormonal level. Since, so far, no end of the bone loss in space has been detected, and since this effect is partially irreversible, this is probably the most dangerous physiological change observed in response to microgravity. Bone loss goes along with loss of mass in related muscles, and with the risk of kidney stones and calcification of tissues in the long-term. The dynamic equilibrium between bone growth and destruction/resorption is disturbed by the changed mechanical stress of the bone and by altered segregation activities of hormones and changed efficiency of vitamins in the blood. Bone renewal is performed by specialised bone cells, the osteoclasts, which remove old bone, and osteoblasts, which generate new bone. Space experiments have shown that exposure to weightlessness of 1–2 weeks results in increased osteoclasts activity and decreased activity of osteoblasts. On the ISS, the ERISTO (European Research in Space and Terrestrial Osteoporosis) MAP project is oriented towards biochemistry at cellular and whole organism-level including genetic mechanisms. The knowledge gained by this research will probably contribute to ease the severe problem of osteoporosis of elderly people on Earth (it is estimated that about 50% of women and 15% of men above 50 years of age suffer from a fracture of hip, wrist or spine due to osteoporosis).

(d) *Muscle Atrophy in Space:* Past space experiments have shown that in muscles the physiological changes induced by microgravity comprise loss of mass, force, power and increased muscle fatigue. On Earth muscle atrophy is a consequence of bed confinement, casting, injury and trauma, reduced physical activity and ageing. The space environment provides a unique environment to study the effects of long-term muscle disuse on muscle function, physical performance and health. Research projects that include the development and testing of countermeasures on ISS astronauts are underway. In the past, the limited number of astronauts available as test subjects was a problem, but this should no longer be the case when the ISS crew consists of six astronauts. The countermeasures under consideration are resistance exercise, lower-body negative pressure, aerobic exercise, penguin-suits, drug treatment, electric stimulation and flywheel ergometer exercises. ESA has developed two facilities for this research on the ISS, namely: MARES (the Muscle Atrophy Research and Exercise System), and FLYWHEEL which will measure muscle strength of all major muscle groups. These will be used to evaluate, in space, the effectiveness of different countermeasures regimes, which are of critical importance for long-duration space missions.

(e) *Changes to the Nervous System/Human Sensory and Balance System in Space:* The nervous system is one of the areas most affected by gravity. It is the most complex and least understood part of the human body and includes the brain, spinal cord, peripheral nerves and the sensory organs. This system controls blood pressure, maintains balance and posture, coordinates movements and regulates sleep. Entering microgravity, astronauts suffer a disturbance of their vestibular system, their acceleration sensing system, which is accompanied for most astronauts by a motion sickness known as "Space Sickness", which lasts for about 3 days. This is caused by the provision of inconsistent information from the eyes and the vestibular system. After 3 days the nervous system has learned orientation with visual inputs alone. Research in the field of motion and posture has made major progress in the last 20 years, mainly due to access to the microgravity environment. Millions of people suffering balance disorders on Earth have benefited from the unique insight that vestibular research in space has gained, and from the clinical use of new diagnostic instruments such as the video oculograph, human rotators/centrifuges, and 3-D eye trackers that have been developed in Europe for research in microgravity. For example, the 3-D eye tracker has found wide application in eye clinics for strabismus/squinting operations of swivel-eyed children

3.2. Physical sciences and applications in space

Gravity induced phenomena play an important role in many fields of physical sciences. The European physical science activities under microgravity conditions have predominantly been performed in the frame of Shuttle/Spacelab missions, and by short duration precursor experiments with various types of sounding rocket in the 1980's and 1990's. This research had been deliberately focussed by the scientific community upon selected topics that combine scientific interest with the potential for improving industrial processes. The transfer of results to terrestrial applications from two decades of microgravity research on board Spacelab, MIR and sounding rockets has now begun. This transfer concerns fundamental knowledge on physical processes in metals, crystal growth, fluids and combustion, and continuing research in these fields on the ISS will accelerate the transfer rate.

The achievements, and future plans, of some selected areas of research are outlined below:

3.2.1. *Solidification processes*

In solidification processes from a melt the growing microstructure of the solid determines the physical properties (e.g. the mechanical, electrical, chemical and magnetic characteristics) of the material. The control of material structure during the liquid-to-solid phase transition is absolutely crucial for the quality and reliability of materials produced, for example, in the foundry and casting industry. Past experiments in microgravity have yielded better uniformity and lower defect densities of the solidified materials. On the ISS it is planned to investigate the processes at the phase interface such as melt flow, under-cooling, solidification velocity, curvature etc and the role that gravity plays in these processes.

Another important aspect for research on solidification processes is the validation of numerical models. In industry many models have been developed to simulate the flow fields in metallic melts, but experimental methods to verify these models are either totally missing or very complicated to evaluate due to gravity-induced turbulence phenomena. Processing metallic melts under weightlessness in a space laboratory could help to validate these models and to verify their reliability.

3.2.2. *Thermo-physical properties*

On Earth the measurement accuracies of thermo-physical properties are in the order of 50–100%, which presents a major problem for industry which vigorously demands better input data for their numerical simulations. Only with data of higher accuracy can improvements in casting control, efficiency and product-quality be achieved. With levitation techniques (used to eliminate contacts between highly reactive metallic melts and a crucible) in microgravity, where the electromagnetic or electro-static positioning forces needed for levitation are about three orders of magnitude smaller than on Earth, strongly improved accuracy (by up to a factor of 10) in the determination of thermo-physical properties of metal melts can be achieved. In addition, the smaller positioning energy needed in space makes it possible to enlarge the temperature range (i.e. to the range 400–2200°C), so that it covers a variety of commercial alloys (e.g. aluminium, copper, titanium, steel and nickel alloys).

On the ISS the thermo-physical properties to be measured will be: melting range, density, surface tension, viscosity, heat capacity and enthalpy, thermal conductivity and diffusivity, and electrical conductivity. In metallurgical industries the major applications of such improved thermo-physical data are in the production/casting of iron, steel, and a wide range of alloys. In Europe, more than 10 million tons of castings are produced per annum, generating a turnover of 18 billion Euros. The competitiveness of the European companies relies upon the industry's ability to produce higher performance materials and to improve processing practices.

3.2.3. *Crystal growth of semiconductor materials*

Single crystals of semiconductors are the very basis of the electronic age. Electronic components such as integrated circuits are made of semiconductor wafers of single crystals. Single crystals are grown from a melt, from solution, or from vapour. Unfortunately single crystals often contain defects and dislocations in the regular layer of atoms, as well as inclusions and impurities. Technical applications require continuously increased device densities to reduce mass and volumes (e.g. of mobile phones) and fewer defects to increase their technical performance. On Earth gravity induced heat and mass flow influences the growth process and crystal perfection and the number and density of defects. The main reason for performing crystal growth experiments in space is to understand the basic transport mechanisms that determine the final properties of the crystal grown. The microgravity environment provides the ultimate conditions for controlling the transport phenomena in crystallisation processes that are characterised by diffusion controlled heat and mass transfer.

Past experiments on Spacelab distinguished between gravity induced convection and surface tension induced flows. Much larger crystals of gallium arsenide than are possible on Earth have been grown, and it is also possible to generate and stabilise the large liquid floating zones needed to grow larger single crystals of silicon, the material from which most electronic components are made. Crystal growth in space makes it possible to prepare samples showing the intrinsic (i.e. the best possible) properties of the semiconductor materials. Such benchmark samples are invaluable for assessing the required investment in the development of new semiconductor devices. An example of this is the planned growth of CdTe single crystals on the ISS, the basic material used in highly sensitive X-ray and gamma ray detectors. The objective is low-dosage X-ray irradiation of patients, and more sensitive identification of flaws in high performance materials.

3.2.4. *Fluid science in space*

Based on results from past experiments in space it is planned to perform measurements on the ISS of heat transfer, mass exchange and chemical processes in multiphase systems and supercritical fluids. Also diffusive processes in mixtures will be measured and the stability of foams and emulsions investigated. Applications of this research include the development of reactors for supercritical oxidation of industrial contaminants and high-efficiency heat exchangers, as well as the improvement of reactor design in industrial plants and of oil recovery techniques.

A practical example of fluid science applications is the enhancement of crude oil recovery methods. Crude oil is one of the most important resources on Earth, because our power generation and transportation depends largely on refined petroleum, and because a wide variety of products are made from petrochemicals. Crude oil is a non-renewable resource and therefore oil companies are continuously seeking ways to recover as much as possible from existing sources, and to exploit new reservoirs more efficiently. Near-surface reservoirs are almost depleted and at present it is necessary to drill to a depth of 7 km to find new oil deposits. When a new reservoir has been found, a large number of very expensive (up to 100 million Euro each, if offshore) exploratory wells will normally need to be drilled to determine the size of the reservoir and the composition of the crude oil. In order to reduce the number of drills, petrochemical companies try to apply thermodynamic models. These require geophysical/geological data, but most importantly they also require precise data on isothermal diffusion coefficients and thermo-diffusion (Soret) coefficients of a few crude oil samples from the reservoir. The crude oil at such depths is under very high pressure (500 bars) and high temperatures, so that the conditions are supercritical below 4 km. In addition the crude oil is a multi-component organic mixture for which diffusion coefficient measurements do not exist but need to be made. Since the accuracy of laboratory measurements on Earth is affected by gravity-induced buoyancy and convection, it is not possible to conduct the diffusion coefficient measurements that distinguish more than two components of the crude oil. This problem has been overcome in the past by measurements of these coefficients during space missions in microgravity and oil companies are very interested that such measurements continue on the ISS.

3.2.5. *Combustion*

Combustion is the process of transforming chemical energy into thermal energy (heat). This process is vital for our daily lives for both industrial and domestic use. Gas driven turbines produce electricity, gas fires heat buildings, and gas combustion powers cars, ships, aircraft and rockets. Humanity is currently dependent on finite, non-renewable fossil fuels for energy and heating. The combustion of fossil fuels is inherently connected with the production of pollutants as exhaust by-products. Some of these, such as carbon monoxide and soot, are harmful to humans. Others, such as carbon dioxide, and oxides of sulphur and nitrogen, are involved in complex chemical reactions in the atmosphere which influence global climate. The world consumption of fossil fuels is expected to rise in the coming decades. Therefore it is imperative that industry does its utmost to increase combustion efficiency and reduce pollution. However, present numerical software models designed to solve these problems are of very limited usefulness, since experimental data obtained on the ground are influenced by gravity-induced convection and natural diffusion, making optimal solutions difficult. On Earth, strong convection and buoyancy forces disturb the combustion processes because a large temperature rise during combustion leads to dramatic local density changes, and often to turbulent flows in and around the flames.

The microgravity environment enables the study of stable flames, which significantly helps the understanding of fundamental physical and chemical processes involved in combustion, and facilitates better mathematical modelling. This in turn leads to an optimisation of combustion processes on Earth. Data from past experiments under microgravity conditions have resulted in marked improvements of the simulation models used in industrial combustion process design. Past microgravity combustion experiments, and related modelling, have led to a new understanding of basic combustion phenomena, and the role of the different heat- and mass-transfer parameters in convection, diffusion and radiation is now much better understood. Future planned experiments on the ISS will involve droplet and spray evaporation, auto-ignition conditions, and soot formation in flames. In line with the political guidelines for protection of the Earth's environment, the principal research objective is to improve combustion efficiency and to reduce pollution by power plants and engines.

3.2.6. *Fundamental physics*

There is now a growing interest in using microgravity to investigate various aspects of fundamental physics. Research projects in the field of complex plasmas already started in the mid-1990's with sounding rockets, the Space Shuttle (STS-95 in 1995), and recently on the ISS, and these will be extended. Experiments on cold atoms/atomic clocks in space and on the interaction of cosmic and atmospheric particles are also planned on the ISS. Some of these experiments are described below.

(a) *Complex Plasmas:* Although plasma is one of the major constituents of the Universe it is not widely recognised on Earth since it is made up of invisible, charged particles. In the last 10 years, worldwide scientific interest in "complex plasmas" has been growing as researchers have discovered new and unusual liquid and crystalline plasma states. Complex plasmas consist of ions, electrons and charged micro-particles (each individually visible because they are about 50,000 times larger than a plasma ion) which enable scientists to visualise the kinetics of plasmas for the first time. These micro-particles also increase the complexity of the plasma and slow down the plasma dynamics. In this state, the plasma physics becomes optically observable with a powerful microscope, and allows investigation of the liquid and crystalline plasma states. However, since the micro-particles are relatively heavy, gravity is the dominant destructive force in these complex plasmas. Therefore precursor experiments have been performed under microgravity conditions using sounding rockets and Shuttle flights, and recently on the ISS. These experiments have allowed scientists to study many aspects of complex plasmas, such as the 3-D self-organisation of matter, fluid physics at particle level, flow around obstacles and through a constriction (nano-jets), interpenetrating flows, coalescence of two liquids, plasma drops, crystal growth at the particle level, interfacial melting, etc. At the early state of this research all of these experiments need specially trained astronauts to adjust parameters, update or exchange equipment, and observe the experiment. Recent experiments on the ISS resulted in the discovery of coagulation of micro-particles to super-aggregates. Numerous applications on Earth are expected from this research. Examples include nano-particle filtering for cleaning contaminated fluids, plasma deposition for improved surface coatings (e.g. self-lubricating surfaces), the design of new composite materials, polymer solar cells, and bio-plasma physics (e.g. sorting of bacteria for cell cultures and the killing of harmful bacteria).

(b) *Cold Atoms/Atomic Clocks in Space:* The European plan to accommodate the ACES (Atomic Clock Ensemble in Space) on the external platform of the Columbus Laboratory is of considerable importance in the context of both fundamental and applied physics. The laser-cooled atomic clock will provide ultra-precise measurements of time, attaining accuracy levels 10–100 times higher than on Earth. The laser light cooling reduces the thermal velocity of atoms to a few centimetres per second, which corresponds to a temperature of 1 micro Kelvin. Under microgravity conditions the caesium atoms remain at these velocities, while on Earth the gravitational acceleration increases their speed rapidly (in 0.1 second to 1 m per second) when the lasers are switched off for signal interrogation. This leads, in space, to a narrow resonance and a high signal to noise ratio. Thus laser cooling in microgravity results in a 100–1000 times longer interaction time than on Earth. It is expected that this atomic clock will reach a frequency stability that is one to two orders of magnitude better than can be achieved with the most advanced clocks on Earth. Atomic clocks in space are of particular interest in future navigation systems (e.g. Galileo), where the accuracy of a navigation system depends directly on the timing accuracy of its reference clock. They will also provide a unique, universal time reference for basic physics (e.g. checks of relativity theory) and other applications such as geodesy, Earth observation and telecommunications.

4. The Future of European Human Spaceflight

4.1. ISS operations

A key priority of European human spaceflight activities remains the effective use of the ISS in the next 10 years in order to maximise the return on European investment. In view of the planning of long-duration human exploration missions it is imperative that the ISS is used for the preparation of these new endeavours. The ISS is ideally suited for testing hardware developments, and to perform long-term medical studies, related to future exploration missions to Moon and Mars. These medical studies on humans will be focused on the long-term effects of microgravity, radiation biology, and the psychological effects of long duration flight.

4.2. A European scenario for the exploration of the solar system

Since the end of the 1990s, ESA has been preparing its next steps of robotic and human space exploration in the frame of the Aurora programme. It is the principal objective of the Aurora programme to perform robotic missions to Moon and Mars for scientific purposes, and to prepare for later human missions to both targets. The ultimate goal for Europe in this context is to participate as a partner in a global, international space exploration endeavour to allow European astronauts to reach Mars by the end of the third decade of the 21st century. Based on a Call for

Exploration Ideas in 2001, ESA internal and industrial studies, and the recommendations of EPAC (Exploration Programme Advisory Committee), the preliminary European priorities and objectives of Aurora were defined. In the short term, Aurora features robotic missions while at the same time preparing for future human exploration missions. These missions are considered necessary to acquire scientific and technical knowledge, and especially to further the development of European robotic exploration capabilities. The first key missions of the Aurora programme are the Mars Exobiology Mission (ExoMars) and the Mars Sample Return Mission (MSR). The ExoMars mission will characterise the Mars biological environment, search for traces of past and present life, and identify possible hazards before landing other spacecraft or humans.

The Mars Sample Return mission is a mission of the highest scientific interest, and is the first robotic mission that is directly relevant to a human mission to Mars. The goal of bringing back the first sample of Martian soil is a major technological challenge. In the present concept, the MSR mission will consist of two composite spacecraft. The first includes an Orbiter and a Re-entry Capsule, and will be placed in a Mars orbit waiting for the Mars Ascent Vehicle (MAV) to bring the soil samples into orbit. The second spacecraft, to be launched 2 years later, will include a cruise stage carrying the Descent Module (DM) and the MAV towards Mars. The DM will land on the Martian surface where the samples will be collected and stored in the MAV, which will bring them to orbit. After docking with the Orbiter the samples will be transferred from the MAV to the Return Capsule.

Based on the European heritage in human spaceflight, ESA is currently also assessing its future priorities for the development of human spaceflight capabilities required for the exploration of the Moon and Mars, including habitation, transportation and robotics. In particular initial steps have been taken to analyse potential cooperation with Russia for the development of a human transportation capability.

5. Conclusion

Considering the relative youthfulness of European human spaceflight, significant technical and scientific progress has been achieved. The launch of the European Columbus laboratory planned for 2006/7 will pave the way for the implementation of a significant ISS utilisation programme which will further advance technical and scientific progress. Future human spaceflight activities, in particular related to the exploration of Moon and Mars, will increasingly be integrated with robotic exploration missions following a strategy that builds on the complementary skills of humans and robots in space.

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Discussion

Mr. Rodney Buckland (Open University): Is it possible to do a convincing ‘‘cost-benefit’’ analysis of, say, the development of medical technology arising from space technology?

Mr. Hufenbach: Within the framework of the European space effort, some 4 billion Euros/year have been pumped into the European economy for about two decades. An important part of that amount is used for the development of leading edge technology to support ESA's space programmes. Spaceflight developments require novel technical solutions for an extreme environment. This has created new products in terms of materials, instruments and services. Some of these advanced technology developments find their way into applications other than just the space applications originally intended. However it often takes several years for a new space technology derived product to be transferred into a marketable product or service on the ground.

The benefits from space activities are often ‘‘spin-offs’’ such as medical instruments, new materials useful for industrial production, and new processing techniques. In the area of life and physical sciences, ESA, assisted by industry, performed an ‘‘identification study’’ between 1999 and 2001, which included an estimate of the market potential of related spin-offs. The outcome of this study revealed 14 different technical items, mainly in the area of medical instruments derived from instruments developed for space life science investigations, that were already on the market. In 2001 the estimated value of these 14 spin-offs amounted to 60 million Euros, and in 2003 was 100 million Euros. Thus in 2003 the revenue associated with these spin-offs exceeded the actual annual public funding spent by ESA in the field of space life and physical sciences. Specific examples in the medical care field include:

- A "selftonometer" for routine monitoring of the ocular pressure in glaucoma patients
- A bone densitometer ("Osteospace") based on ultrasound instead of X-rays
- "Video Oculograph" for the measurement of eye orientation and corrective eye surgery for swivel eyed children
- A "Respired Gas Analyser" to determine cardiac output and lung characteristics and functioning; and
- "Sterilite", an ozone gas based disinfection system for biomedical instruments

There are many more such spin-offs, details of which can be found in the following ESA publications on Space Technology Transfers: "Fitness, Leisure and Lifestyle", ESA BR-184(VI); "Medicine I", ESA BR-184 (VII); "Medicine II", ESA BR-184 (IX); "Babyguard", ESA BR-184(X); and "A Thread from Space to your Body", ESA,BR-184 (XIV).

Professor Bernhard Foing (ESA): The president of India unveiled his vision of exploration of the Moon "for all human kind" at Udaipur on 23 November 2004. Japan is also preparing a roadmap for space exploration. How do you think that the international community can best harmonise its human spaceflight objectives?

Mr. Hufenbach: In the political/social context, multi-national exploration programmes will help enhance international cooperation, and as a consequence the world might become more peaceful. In the longer term, the creation of a permanently manned outpost on the Moon may be seen as the first stage in the spread of human culture across the Solar System. A global space exploration programme should be initiated, with wide-ranging international discussions to design and test appropriate new multi-cultural governance and organisational structures for its management, development and financing.

Dr. Patrick Magee (Royal United Hospital, Bath): A comment: opportunities for UK citizens to work in ESA are limited by the low level of UK contributions to ESA, especially in human spaceflight. Michael Foale and Piers Sellers had become US citizen to become NASA astronauts. Thus UK interests are not fostered by sitting on the sidelines.

Mr. Hufenbach: Since the UK has decided in the past not to participate in ESA's Columbus Programme, which represents the European contribution to the ISS, ESA has not invited British candidates to become members of the European astronaut corps. However, British scientists do participate as co-investigators in the research programmes associated with human spaceflight.

Professor Steve Miller (UCL): You mentioned the inspirational effect of the Apollo programme in terms of the increased numbers of young people taking up postgraduate studies in science in the late 1960s and 1970s. Your suggestion was that Britain would benefit from a similar increase in student interest if the UK were involved in ESA's human spaceflight programme, as well as there being an increased general public interest in science. Countries like France and Italy are already involved in human spaceflight programmes, but I am not aware of a great difference between France and Italy, on the one hand, and the UK, on the other, in terms of public interest in science. Like the UK, France and Italy are also suffering from a relative decline in student interest in the physical sciences. So my question is: if involvement in human spaceflight is inspirational in the way you suggest, why does this effect not show up in international surveys of public interest in science and in terms of students enrolling for studies in the physical science studies? A suggestion is that ESA might want to conduct a more focussed in-depth study of this question to see whether or not this inspirational effect is actually present, perhaps hidden beneath the raw statistics.

Mr. Hufenbach: It is a proven fact, based on statistical data, that the Apollo Programme inspired younger generations of peoples across the world to take greater interest in technology and natural sciences, a prerequisite for flourishing economies. However, there is a difference between the Apollo Programme of the 1960s and 1970s, an achievement, which is recognised as one of the most spectacular technical performances in the history of mankind, and the human spaceflight programmes in the 1980s and 1990s. The 1980/1990s manned spaceflight activities were not interplanetary missions, but had the objective to exploit the environment of Low Earth Orbit using retrievable transportation vehicles, like the Space Shuttle and Soyuz, and orbital laboratories like MIR, Spacelab and the ISS. Nevertheless, with respect to the specific question of a presently existing difference of interest in science in the UK and in France/Italy it might, as suggested, be useful to perform a focused study based on statistical data, which might be available through the EU.

The situation has now changed dramatically. At the beginning of 2004, President Bush announced a new Space Exploration Vision, starting with a return to the Moon by 2020 in preparation for the human exploration of Mars and other destinations in the Solar System. Mr. Bush intends to invite the space-faring nations of the world to participate in this new space exploration programme. Recently, the new NASA Administrator, Michael Griffin, has criticized the past space policy of NASA, and especially its failure to continue with human space exploration after the Apollo Programme. He regretted that a lot of exploration experience has been lost over the last three decades, and confirmed his commitment to the new Vision. It can certainly be expected that the first human landing on Mars will have a similar inspirational effect as the Apollo Programme had in 1960s and 1970s.