Biology in Space and Life on Earth

Effects of Spaceflight on Biological Systems

Edited by
Enno Brinckmann

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ESA Astronaut Ulf Merbold floating above the Glove Box of the Biorack facility during the first International Microgravity Laboratory mission (IML-1, STS-42) inside the Spacelab Module.
Courtesy NASA (1992)

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Contents

Foreword

Flying into space still is an endeavour very much at the fringes of technical feasibility, but the same time it pushes the horizon of mankind's experience into areas unknown so far. In this respect it continues the efforts of our ancestors to explore the world. Men like Marco Polo, Columbus, Vasco da Gama, Livingston, Cook, Amundson are representative for the human spirit so well described in Johann Wolfgang Goethe's drama "Faust", never to be satisfied with what we know, but rather to be driven to go further and to explore "terra incognita" in order to know more. Whether human curiosity is genetically programmed or there are other reasons, that we persistently are striving to understand the world better and better, might still be an open question, but there is no doubt, that it is the essence of philosophy and science.

At present it is for the first time in human history that we have the tools in hand to leave Earth behind at least temporarily. Considering the many contributions to our knowledge made by our ancestors with much less sophisticated tools I feel strongly that we, the now living generation, have no choice. We must take up the challenge of space exploration. Although there is always room to do more, I feel that essentially we are on the right way to live up to it. NASA's moon flights for example mark unique milestones in human history. Regarding the expansion of knowledge I think we also have been very successful by sending fairly elaborated unmanned space probes to the planets of the solar system. The knowledge we acquired in this way is many times more detailed than the knowledge accumulated during all centuries prior to the short era of spaceflight. Although a lot of work is still to be done, I am certain that within the first half of this century astronauts, respectively cosmonauts will fly to Mars. It is also evident that in addition to the exploration of space, particularly of the solar system, the scientific utilization of the unique space environment will be on mankind's agenda. In fact ESA started already decades ago to perform scientific investigations in space by exploiting microgravity and other unique features of space, e.g. the absence of atmosphere and the global view from orbit.

A visionary decision taken by ESA in seventies of the last century was to contribute to NASA's Space Transportation System by providing Spacelab. This element, in fact a full toolkit designed and built in Europe, converted NASA's Shuttles from transporters into laboratories suitable for a huge variety of scientific investigations including biology and human physiology. As a European astronaut on Spacelab-1 and on IML-1 with "Columbia" I am happy that Spacelab functioned flawlessly, whenever it was in orbit. The same time I regret that we did not adopt a credible European Spacelab-utilization programme, although many fascinating experiments were performed on several flights. By now the International Space Station is on line. Although for the near future first priority is given to its assembly, it will become the most sophisticated laboratory in orbit, as soon as its assembly is completed. Other than Spacelab it will be in orbit not only for a week or two, but for years. Its novel features will provide many more opportunities to the scientific community to do research in orbit.

Reviewing the scientific investigations performed in the last decades clearly reveals that microgravity turned out as the most relevant asset for gaining new insight. Experiments in human physiology and biology in particular led to many new conclusions and pushed the horizon of our knowledge. A number of studies in these disciplines were based on the astronaut's body as test object. In many cases like on ESA's Euromir'95 mission, we scientist-astronauts had to draw blood samples on each other or place electrodes on our bodies in order to acquire physiological data. Perhaps it was for that reason that most of us developed a special interest in many studies dealing with biological problems. In addition it was also evident, that the insight acquired usually had the potential of direct benefits. If we deepen the knowledge with regard to the metabolism of bones there might be a short way to improve the treatment of osteoporosis. Experiments bringing light into the mechanisms of human immune response also have a potential to finally improve the quality of life by finding new ways to stimulate its power. There are many other areas of research focussing on human physiology as well as on plant physiology, on bacteria, on cells, insects etc. Considering the full spectrum of scientific questions related to space flight biology is one field out of many others, but evidently it is one of the most important areas and definitively one of the most dynamical. The current publication "Biology in Space and Life on Earth" is a comprehensive presentation of the relevant research work performed at present.

Ulf Merbold

Preface

Space and Biology – this combination of terms is not very common in science despite the fact that biological phenomena in the unique environment of weightlessness have been analysed from the early days of space flight up to now. The exploration of Space required investigations in an area beyond the experience of man living on Earth: the border presented by the long-established environment of gravity had to be crossed, and, as in the rising era of steam trains when people were questioning the ability to survive in these high-speed vessels, one could not imagine the impact of zero gravity and Space radiation on any organism during space flight.

After more than 40 years of Space research we have a better understanding now about life in weightlessness. The authors of Chapters 4 and 8 summarize the unique results in plant root physiology and in cells of the immune system collected in their experiments over a period of 12–30 years. This wide timeframe indicates a typical fact of Space research: the frequency of experiments is very low, not days or weeks as in typical ground investigations but rather months or years due to the rare flight opportunities, the complex preparation and the many controls, all of them also having an impact on the costs of experimentation in Space. The transfer of an experimental idea from the common ground-based laboratory to the Space environment is usually combined with many tests to prove that the situation in orbit is comparable to that on the ground. Potential failures and side effects are described in Chapter 1, where the basic terms are also defined, especially the term "microgravity", which is very often used by the science community of gravitational and Space biology to describe the near weightless environment in an orbiting spacecraft. From the perspective of a Project Scientist, however, who was responsible on behalf of the Space Agency for a complete experiment from proposal until the final hand-over of the Space-flown samples to the investigator, these reviews allow one to look upon the subjects of investigation from a different angle – the big picture!

We share this perspective with our readers not only from the historical point of view, although right now experiments in Space biology are entering a new era with the International Space Station (ISS), after the retirement soon of the Space Shuttle as the main carrier for numerous experiment facilities. Most experiment platforms are accumulated now on the ISS, with a few others on satellites. The logistics and the experiment protocols are different on the ISS – more complex, on the one hand, but larger exposure to near weightlessness and Space radiation is possible on the other hand. These expectations will influence future research and our authors reflect these aspects in their conclusions and outlooks.

The other topic of this book is related to “Life on Earth”. It was our aim to demonstrate that experiments in Space are not a solitary research field but are bound into a wide spectrum from ground-based fundamental research to application-oriented medical research. Chapters 2–4 discuss in detail the mechanisms affecting the orientation of plants in the gravitational environment. The progress achieved in this part of plant physiology was not possible without the experiments under reduced gravity in low Earth orbits. The reaction chain between the gravity stimulus and the cell-internal response can be described much better now with recent discoveries achieved in Space experiments – many pieces of the mosaic have been collected and implemented, either by falsifying a previous hypothesis (e.g. Chapter 4, Section 4.2.2) or by adding new evidence from facts previously unknown due to the permanent interference of gravity in ground-based experiments.

Human health research has also gained by space flight: Chapters 5–8 analyse investigations in the field of connective tissues, bone metabolism and immune system.

The widely spread bone loss or osteopenia by ageing or by disease, osteoporosis, is accelerated tremendously in weightlessness and is, therefore, a research objective not only in astronauts but also in cellular models, in which the primary reactions and the potential cure of bone loss can be investigated. Removal of the gravitational force is a perfect way for short-term experimentation with cell cultures, allowing deep insight in the primary processes of tissue formation (Chapter 5), bone formation (Chapters 6 and 7) and immune cell response (Chapter 8) *in vitro*. Whilst it seems obvious that the reduction of mechanical loading leads to bone loss (like on Earth during prolonged bed rest), it is not at all evident that cells of our immune system respond to gravity, which has been present during their entire evolution on Earth. Chapter 8 analyses this mysterious phenomenon that was already observed on astronauts in the very early days of human space flight.

Chapters 9 and 10 concentrate on the other feature of space flight: Space radiation and its impact on organisms and isolated cellular systems. Chapter 9 describes one kind of technological approach for radiation research in Space and on ground, focussing on radiation damage of the DNA in single cells. Chapter 10 extends this aspect of radiation research to general questions, ranging from evolution to the habitability of Mars.

We hope that the reader gets a good overview of past and current achievements in this comprehensive description of biological research in Space. Since most of the Space experiments described in the following chapters were performed in facilities of the European Space Agency (ESA), the Introduction summarises typical mission scenarios and describes ESA’s experiment platforms for biological research in Space.

Enno Brinckmann
Leer, July 2007

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Introduction

1
Flight Mission Scenarios

This section overviews the various missions that have provided platforms for the experiments presented in this book. In general, there have been four kinds of flights:

(1) parabolic flights in an aircraft with multiple periods of 20 s weightlessness;
(2) sounding rockets with 5–15 min experiment time;
(3) manned space flight missions with 7–16 days in orbit;
(4) robotic missions in unmanned capsules for 12–15 days in orbit.

Tables 1–3 summarize mission data and give a selected list of experiments. Each mission is identified by its flight number and contained several payloads: only those payloads listed here have been used for the experiments described in the following chapters. The selected experiments are given with their dedicated name, sometimes in connection with an identification number, and their Principle Investigator or team leader. The mission scenarios on the different carriers are not only distinguished by the duration of their free-fall (or microgravity) conditions but also by the required ground logistics before (= late access) and after the flight (= early retrieval); this is an important factor when fresh samples with limited life time have to be transported into Space and when the returning samples cannot be preserved in a stable condition or need immediate treatment after landing, e.g. behavioural studies on live animals.

Table 4 shows the late access time for all carriers, indicating that latest moment when the experiment has to be handed over in its flight configuration to the ground personnel for integration into the spacecraft, varying from a few hours to days. Sounding Rockets have a very late integration time due to their less complex payloads complement. The stowage compartment in the Space Shuttle Middeck cannot be loaded with experiments later than 17 hours before launch due to safety precautions, since the countdown has to continue with liquid fuel tanking of the spacecraft. The situation with the Foton satellite is different: the payload has to be

Table 1 Sounding rocket missions with payloads relevant to some experiments described in this book. TEM: Texus experiment module; CIS: cell-in-space module; BIM: biology in microgravity.

Flight	*Date*	*Payload*	*Investigator (country)*
Maxus-1B	8 NOV 1992		Cogoli (CH)
Maxus 2	28 NOV 1995	TEM 06-5MZ	Cogoli (CH)
Maser-3	10 APR 1989	CIS-1	Cogoli (CH)
Maser-4	29 MAR 1990	CIS-2	Cogoli (CH)
Maser-5	9 APR 1992	CIS-3	
Maser-6	5 NOV 1993	CIS-4	
Maser-7	3 MAY 1996	CIS-5, EMEC	
Maser-9	16 MAR 2002	CIS-6	
Maser-10	2 MAY 2005	BIM-1	
Texus 18	6 MAY 1988	TEM-KT	Volkmann (D)
Texus 19	28 NOV 1988	TEM-KT	Volkmann (D)

integrated into the satellite before the satellite is mated with the launcher rocket, which happens two days before the launch. However, only a few small items without electrical interfaces to the satellite can be placed into the capsule on the launch pad around 12 hours before launch through a special hatch, which gives access to the payload located directly behind the hatch; all other payloads cannot be accessed by that time.

The situation is better for the Soyuz missions, where a late integration of payloads not heavier than 10 kg is possible a few hours before the crew climb into their seats. During past Soyuz missions and Foton-11, however, all items had to be transported to the launch site via Moscow to allow for customs inspection and required additional time for the subsequent transport to the launch site, which extended the late access time for live samples considerably. Only recently has some preparation of experiments been possible at the launch site in Baikonur (Kazakhstan). During the two-day flight period to the International Space Station (ISS), experiments in Soyuz were either inactive or limited to automatic functions: specific interaction by the crew was in general only possible after docking to the ISS, which added, for most samples, two more days to the storage period after handover. During descent, the Space Shuttle was usually equipped with ambient and cold stowage compartments, whilst the temperature for samples returning from ISS in the Soyuz capsule was not actively controlled, resulting in temperature peaks up to 31 °C.

Experiment integration into sounding rockets was possible until one hour before launch; however, the period of weightlessness was limited to 6, 6 and 12 minutes for Texus, Maser, Maxus rockets, respectively [2]. The early retrieval time of the payloads was again beneficial for experiments, as the experiment units were often returned to the scientists within one hour after landing.

Table 2 Space flight missions with crew support in the Space Shuttle (Space Transportation System, STS). Flights 61-A, 42 and 65 were research missions with Spacelab (D-1, German Spacelab Mission; IML-1 and IML-2, International Microgravity Laboratory #1 and #2), whereas flights 76, 81 and 84 were dedicated to activities on the Russian Mir Station with Spacehab in the Shuttle's cargo bay (Shuttle-to-Mir Mission, S/MM-03, 05 and 06). The experiment list is reduced to those described in this book.

Flight	*Date*	*Payload*	*Experiment (investigator)*
STS-9 Spacelab SL-1	28 NOV–8 DEC 1983	Biostack, Portable Incubator	Biostack (Bücker) ES029 (Horneck) AO5/17/LS/CH (Cogoli)
STS-61-A (22) Spacelab D-1	30 OCT–5 NOV 1985	Biorack	19-D DOSIMETR (Bücker) 32-CH BLOOD (Cogoli) 33-CH LYMPHO (Cogoli)
STS-40 Spacelab SLS-1	5–14 JUN 1991		781240 (Cogoli)
STS-42 Spacelab IML-1	22–30 JAN 1992	Biorack, LSLE freezer, Photobox	02-NL BONES (Veldhuijzen) 10-D MOROSUS (Bücker) 12-D DOSIMETR (Reitz) 14.1-CH FRIEND (Cogoli) 14.2-CH HYBRID (Cogoli) 14.3-CH CULTURE (Cogoli) 20-F ROOTS (Perbal)
STS-55 Spacelab D-2	24 APR–6 MAY 1993		RD-BIOS (Reitz) RD-UVRAD (Horneck)
STS-65 Spacelab IML-2	8–23 JUL 1994	Biorack, LSLE freezer, NIZEMI, Biostack	01.1-I ADHESION (Cogoli) 01.1-I MOTION (Cogoli) 08-NL BONES (Veldhuijzen) 12.1-D KINETICS (Horneck) 12.2-D REPAIR (Horneck) 19-D DOSIMETRY (Reitz) 32.1-F LENTIL (Perbal) CRESS (Volkmann) Biostack (Reitz)
STS-76 Spacehab S/MM-03	22–31 MAR 1996	Biorack, LSLE freezer	19-D DOSIMETRY (Reitz) 32.2-F STATOCYTE (Driss-École) 401-D STATOCYTE (Volkmann) 486-D X-RAY (Kiefer)
STS-81 Spacehab S/MM-05	12–22 JAN 1997	Biorack, LSLE freezer, Photobox	19-D DOSIMETRY (Reitz) 23-D CRESS (Volkmann) 89-F GRAVITY (Perbal) 27-D CHARA (Buchen) TEMP (van Loon)
STS-84 Spacehab S/MM-06	15–24 MAY 1997	Biorack, LSLE freezer	22-D BETARAY (Kiefer) 33-D DOSIMETRY (Reitz) 89-F ACTIN (Driss-École)
STS-95 Spacehab	29 OCT–7 NOV 1998	Biobox-4	HUDERM (Lapière) MARROW-4 (Bouillon)

Table 3 Space flight missions in unmanned satellites. The European Retrievable Carrier (EURECA) was a satellite with automated experiments, launched and retrieved by the Space Shuttle [1]. Bion and Foton satellites were launched with Russian carriers.

Flight	*Date*	*Payload*	*Experiment*	*Investigator (country)*
EURECA	31 JUL 1992–8 APR 1993	Exobiology & Radiation Assembly	Exobiological Unit	Horneck (D) Reitz (D)
Bion-10	29 DEC 1992–10 JAN 1993	Biobox-1	Bones	Veldhuijzen (NL) & Rodionova (UA)
			Fibro-1	Tairbekov (RUS)
			Oblast-1	Alexandre (F)
			Marrow-1	Schoeters (B) & Rodionova (UA)
Foton-10	16 FEB–3 MAR 1995	Biobox-2	Fibro-2	Tairbekov (RUS) & Lapière (B)
			Oblast-2	Alexandre (F)
			Marrow-2	Bouillon (B)
Foton-11	9–23 OCT 1997	Biobox-3	Fibro-3	Tairbekov (RUS) & Lapière (B)
			Oblast-3	Alexandre (F)
			Marrow-3	Bouillon (B)
		Biopan-2	Survival	Horneck (D)
Foton-12	9–24 SEP 1999	Biopan-3	Survival	Horneck (D)

The parabolic flight campaigns provided a completely different scenario. After experiment preparation at the airport (Bordeaux, France), where the Airbus 300 ZERO-G took off, the experiments were taken on board and mounted in their flight position. After a flight of about 0.5 h to the airspace where the parabolic flights were permitted, the experiments could be activated for one or more of the 30 parabolas. Each parabola had 20 s of hypergravity ($1.8 \times g$), followed by 22 s of near weightlessness ($10^{-2} \times g$) and again 20 s of hypergravity ($1.8 \times g$). After about 2 min the next parabola started. During the parabolas the scientists could execute their experiments themselves, analyse data in-flight and change parameters or test objects. Immediately after the approximately 3.5 h long flight, the scientists could analyse their experiments at the airport and prepare the next flight day. Normally, three flight days in a row were performed.

2
Sounding Rocket Experiments

A typical launch campaign of a sounding rocket flight started with the accommodation of the technicians and the scientists at ESRANGE close to Kiruna in Northern Sweden [2]. Well-equipped laboratories were set up to prepare live samples and to

Table 4 General conditions for experiment preparation, start, duration and return for manned and robotic space missions. Experiments on the Space Shuttle and on Soyuz flights to the International Space Station (ISS) could use crew interface for operations; experiments in the Foton capsule and in Sounding Rockets (Texus, Maser, Maxus) were performed autonomously.

Flight	*Space Shuttle (Middeck)*	*Soyuz Flight to ISS*	*Bion/Foton*	*Texus, Maser, Maxus*
Late access before launch	17–24 h	8–12 h	48 h	1 h
Launch site	Kennedy Space Center (USA)	Baikonur (Kazakhstan)	Plesetsk (Russia)	Kiruna (Sweden)
Experiment preparation at the launch site	Full laboratory facility	Limited laboratory facility	No laboratory facility	Full laboratory facility
Experiment start time in orbit	Launch + 4 h	Launch + 4 h (2–3 days)	Launch+ 9 min	Launch +70 s (Maxus: 96 s)
Experiment duration (maximum)	16 days	10 days	12–15 days	Texus: 6 min Maser: 5–7 min Maxus: 12.5 min
Temperature control at descent	Ambient, cooler, freezer	Ambient	Cooler (Biobox)	Experiment provided
Early retrieval at landing site	Landing + 6–8 h	Landing + 2 h	Landing + 1–2 h	Launch + 1 h

load them into their automatic experiment hardware. Integration into the payload platform of the rocket was carried out as late as 1 h before launch (Table 4). The flight duration varied with the power of the rocket motor: the smaller Texus and Maser rockets achieved an apogee height of 250 km and allowed experiments in microgravity for about 6 min, whereas Maxus reached 710 km and had, therefore, a useful microgravity period of 12.5 min. Many experiments were run autonomously in a programmed sequence. Those experiments could be observed by the investigator via a real-time video downlink and could be controlled by telecommand during the flight. At the end of the free-fall period, the payload was spun up and re-entered the atmosphere. This caused very short but heavy and randomly distributed accelerations. At 5 km altitude a parachute opened and returned the payload to the ground with a sink velocity of $8\,\mathrm{m\,s^{-1}}$. The payload was recovered in one piece by a helicopter, which returned it to the launch site within about 1.5 h after lift-off. On request, a second helicopter was provided for immediate recovery

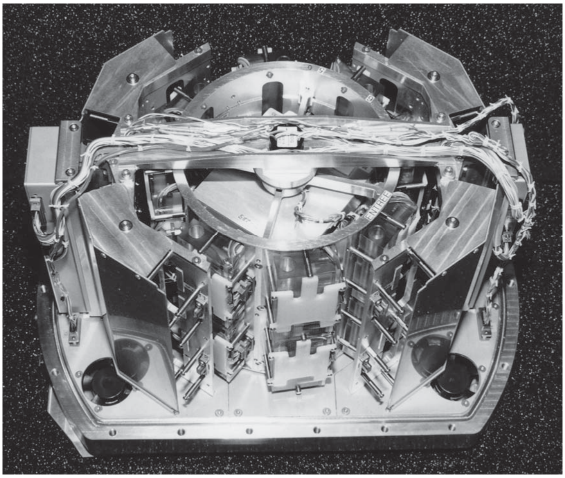

Fig. 1 A typical payload of a sounding rocket: the late access insert (LAI) of the biological incubator module (BIM) as used on the Maser 10 flight for biological experiments. The inner part of the insert consists of a reference centrifuge, which is surrounded by several static racks for accommodation of the experimental units.

of the experiment unit. This allowed a handover of the samples back to the scientists about one hour after launch. Maximum acceleration levels during launch were typically 12×*g* (Maser, Texus) and 13×*g* (Maxus), whilst the microgravity environment was in the order of 10^{-4}×*g*. During re-entry of the payload in the atmosphere, short-term accelerations of up to 50×*g* were possible in all axes, and during impact on the ground shock loads of 50×*g* to 100×*g* could occur.

The experiments were accommodated on circular platforms in experiment-specific modules: Texus Experiment Modules (TEM) were flown on Texus rockets and CIS (cell-in-space) modules on the Maser missions (Table 1). Each module was autonomous; it had its own power supply and electronics unit (Fig. 1). An identical module was often used for biological ground reference experiments. The useful diameter of the experiment deck was 403 mm, the length varied between 160 and 1155 mm, with a mass range of 22–116 kg. These modules provided the desired temperatures for the samples and automated features such as video observation, experiment activation and fixation, control runs on an onboard 1×*g* centrifuge, and data storage or transmission to ground.

3
Biobox on Foton and in the Space Shuttle

The Biobox facility was designed in 1990–1991 for biological experiments on unmanned recoverable capsules of the Bion and Foton type. It was operated in a fully automatic mode, without crew intervention or even telecommanding. After one mission on Bion (Biobox-1) and two on Foton (Biobox-2 and -3), the project was transferred to the US Space Shuttle. After one successful flight on STS-95 (Biobox-4) the career of Biobox on the Shuttle came to a premature end with the STS-107 disaster in 2003 (Biobox-5). A completely re-designed Biobox has been manufactured. Its first flight (Biobox-6) on Foton-M3 is scheduled for launch on 14 SEP 2007 from Baikonur, Kazakhstan. The following information applies to Biobox-1 through to Biobox-4.

Biobox was configured as a programmable single incubator. Experiments sharing that incubator were selected for compatible temperature requirements. On each flight the biological samples consisted of mammalian cell cultures (Table 3), which were accommodated in 30 automatic experiment units, with a standard size of $20 \times 40 \times 80\,\mathrm{mm}^3$ (Biorack Type I container and CIS unit). In each unit, one or two 1-mL cultures could be grown. Culture media, biochemical stimulants and fixatives were contained within these units and could be supplied automatically according to a timeline pre-selected before flight.

From the 30 experiment units, six were placed on a centrifuge that generated 1×*g* acceleration during flight. As an additional reference, a duplicate model of Biobox was operated on the ground almost synchronously with the flight unit. After flight, the results obtained in microgravity were compared with those obtained at 1×*g* (both from the on-board centrifuge and from those on the ground) to identify biological effects specifically linked to weightlessness.

Before launch, the temperature in Biobox was maintained at 20 °C to suppress the growth and development of the cell cultures before entrance into microgravity. The cells were automatically awakened from their dormancy at 9 min after lift-off, when the in-built micro-accelerometer acknowledged the presence of microgravity. At this moment, the centrifuge kicked into action and the incubator temperature was switched to 37 °C, the optimal value for culturing mammalian cells. Later on in the flight, when all cultures had been stopped by adding fixatives, the centrifuge was switched off and the temperature was lowered to prevent the fixed material decaying. All these events occurred automatically, controlled by internal timers. Full automation was retained on the Space Shuttle (Biobox-4), with the crew operations restricted to the occasional cleaning of the Biobox cooling fans' inlet grid.

Nevertheless, the streamlined simplicity of the automated flight operations was off-set by the complexity and ever-changing demands of the mission operations. Note that Biobox-1 was the very first facility of the European Space Agency (ESA) on any Russian carrier [3]. To provide an impression, the as-flown mission scenarios for Biobox-1–4 are briefly described below, since they were all different.

3.1
Biobox-1

With an inconveniently long late access period of 48 h (Table 4), the decision was made to prepare the experiments, as well as the three Biobox facilities (flight, flight spare and ground), in Moscow. For this purpose a pre-fabricated laboratory (called *Moslab*) was set-up in the Netherlands and, after road transport, re-assembled in

Moscow [3]. Loaded with experiments, the flight model of Biobox was ferried by aircraft from Moscow to the launch site Plesetsk three days before launch. The ground model was retained and operated in *Moslab*.

Nine days into the mission the temperature in the Bion capsule started to drift beyond its nominal upper limit of 28 °C. At this point in time, Biobox was already switched to the cooling mode with all experiments completed and all samples fixed. However, the high satellite temperature and the limited air circulation in the capsule compromised the cooling performance of the Biobox. The temperature problems of the satellite not only affected the Biobox and forced the mission controllers to land the capsule two days earlier than planned.

3.2
Biobox-2

Similar to Biobox-1, all flight preparations were carried out in *Moslab*. The telemetry indicated that Biobox-2 performed flawlessly during this flight. After a successful landing, the Foton capsule was transferred by helicopter to the nearest airbase to remove the scientific hardware. Approaching the airstrip, the helicopter was caught by vehement gusts of wind, making the sling-carried Foton capsule swing like a pendulum. The crew was compelled to release the capsule, which fell to the ground from an altitude of 120 m. The capsule and its payload were ruined. The next morning *Moslab* was informed by phone about the crash. Later that day the remains of Biobox-2 were delivered at *Moslab*. The major part of the Oblast-2 experiment was absent and has never been recovered. The two other experiments (Marrow-2 and Fibro-2) miraculously survived the crash, protected by their sturdy experiment containers.

3.3
Biobox-3

Owing to a changing financial and political climate, *Moslab* could no longer be maintained. An alternative ground operations plan was required. All pre-flight operations, including the experiment preparations, were transferred to the ESA facility (ESTEC) in the Netherlands. To send Biobox as late as possible to the launch site Plesetsk, a special aircraft was chartered. After landing in Moscow for customs clearance and refuelling, Biobox was left on the plane while the ESA personnel disembarked for passport and visa clearance. Six hours later the aircraft was back in the air, destination Plesetsk, leading to a complete transportation time (from experiment handover until launch) of 72 h.

The Biobox ground model was retained at ESTEC. When new telemetry was dumped to ground, ESTEC was informed by phone from the flight control centre in Moscow. The telemetry indicated that the FIBRO-3 experiment was not properly executed. Two days after landing (Fig. 2), when Biobox was returned to ESTEC, the failure of FIBRO-3 was confirmed. This was the first and only time that an experiment was lost due to a technical failure in the Biobox facility.

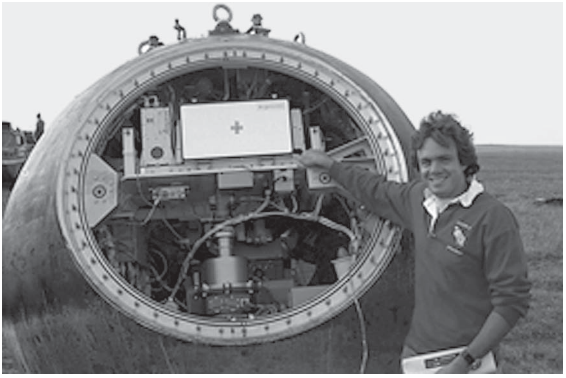

Fig. 2 Foton-11 satellite after landing in the Russian tundra 180 km East of Orsk. The capsule has been opened and the Biobox is visible inside. ESA's Mission Manager P. Baglioni was at the landing site to retrieve the experiments from Biobox-3.

3.4
Biobox-4

After Biobox-3 a new flight opportunity was offered on the US Space Shuttle. Once more, a brand-new ground operations scenario had to be devised. This time, the experiments were prepared at ESTEC in the Netherlands, while Biobox was simultaneously readied at the Spacehab Payload Processing Facility (SPPF) in Florida. The fully prepared experiments, in thermal boxes at 20 °C, were flown three days before launch from ESTEC to Florida for installation in Biobox, which happened 36 h before launch. Despite the better late-access conditions (36 h for Spacehab, 48 h for Bion/Foton), the lead time for the sample preparations was not improved due to the long transatlantic journey. The Biobox-4 ground model was retained and operated at ESTEC.

4
Biorack in Spacelab and Spacehab

Biorack was the first multi-user facility of the European Space Agency (ESA), designed for biological experiments in Spacelab, the European contribution to NASA's Space Transportation System (STS), better known as the Space Shuttle. It flew three times in Spacelab and three times in Spacehab. Spacelab was the European part of the Space Shuttle science programme, whilst the McDonnell-Douglas-built Spacehab was a kind of cargo-carrier that also offered interfaces to experiments. Both modules provided a pressurized atmosphere with environmental control (oxygen, carbon dioxide, humidity). Table 5 shows the environmental data of a typical Spacehab mission [4]; these data were similar during the Spacelab