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ASTROBIOLOGY

# EXPOSE, an Astrobiological Exposure Facility on the International Space Station - from Proposal to Flight

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**Abstract** Following an European Space Agency announcement of opportunity in 1996 for "Externally mounted payloads for 1st utilization phase" on the International Space Station (ISS), scientists working in the fields of astrobiology proposed experiments aiming at long-term exposure of a variety of chemical compounds and extremely resistant microorganisms to the hostile space environment. The ESA exposure facility EXPOSE was built and an operations´ concept was prepared. The EXPOSE experiments were developed through an intensive pre-flight experiment verification test program. 12 years later, two sets of astrobiological experiments in two EXPOSE facilities have been successfully launched to the ISS for external exposure for up to 1.5 years. EXPOSE-E, now installed at the balcony of the European Columbus module, was launched in February 2008, while EXPOSE-R took off to the ISS in November 2008 and was installed on the external URM-D platform of the Russian Zvezda module in March 2009.

**Keywords** Astrobiology · International space station · EXPOSE facility · Low earth orbit · Space environment

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## Introduction

The space environment provides a complex spectrum of physical parameters that are not experienced on Earth and that are of high interest to astrobiology, such as high vacuum and different qualities of radiation. In interplanetary space, pressure reaches values down to $10^{-14}$ Pa; however, in the vicinity of a body — planetary body or artificial satellite — the pressure rises significantly due to outgasing of volatiles from the body. In Low Earth Orbit (LEO), pressure ranges from $10^{-6}$ to $10^{-4}$ Pa. In the cargo bay of the Space Shuttle, e.g., a pressure of $3.99 \times 10^{-5}$ Pa due to outgasing was measured with cargo bay doors open after 100 h Mission Elapsed Time (MET)(Scialdone 1983). The major constituents in LEO are molecular oxygen, hydrogen and nitrogen as well as highly reactive oxygen and nitrogen atoms.

Concerning the origin of cosmic radiation two components can be distinguished: galactic radiation and solar radiation. Galactic cosmic radiation consists of 85% protons, electrons, 14% α-particles and 1% heavy ions of charge $Z>2$ (HZE particles). The solar particle radiation is composed of 90–95% protons, 5–10% α-particles and a few heavier ions. In the radiation belts near Earth, protons and electrons (of galactic and solar origin) are trapped by the geomagnetic field. Solar electromagnetic radiation spans from short wavelength X-rays to radio frequencies. At the distance of the Earth, the average solar constant is 1,360 W $m^{-2}$. Though only 7% of this solar irradiance belongs to the biologically damaging UV range, its effect on life is significant. Whereas on Earth, the stratospheric ozone layer cuts off photons of wavelengths below 290 nm, in LEO the full extraterrestrial UV spectrum is available, including UV-C (190-280 nm) and vacuum-UV (<190 nm).

Space technology has provided opportunities to expose terrestrial specimens, such as prebiotic compounds, organic molecules and organisms, to this unique environment of space or to selected space conditions (Horneck and Brack 1992). Questions to be tackled include:

- the chemistry of precursors of life in space, e.g. in the interstellar medium or in comets;
- the role of the extraterrestrial short wavelength UV radiation, at present absorbed by the Earth's ozone layer, on prebiotic and biological evolution;
- the survival of microorganisms, when travelling in space, e.g. as blind passengers inside of meteorites (lithopanspermia hypothesis);
- the survival of microbial contaminants on space craft on outbound missions to other planets (planetary protection requirements);
- the limits of life.

During previous space missions, such as Gemini, Apollo 16 (Taylor et al. 1974), Spacelab 1 (Horneck et al. 1984a and b), Spacelab D2 (Horneck et al. 1994a; 1996), LDEF (Long Duration Exposure Facility) (Horneck et al. 1994b), MIR (Rettberg et al. 2002), EURECA (EUropean REtrievable CArrier) (Horneck et al. 1995) and several Foton missions (Horneck et al. 2001, Rettberg et al. 2004, Sancho et al. 2007) (Table 1), exposure of various microorganisms to selected or combined space conditions demonstrated the lethal effects of extraterrestrial short wavelength solar UV radiation, but also the enormous resistance of selected species against LEO vacuum when UV shielded (Horneck 1998). Recent experiments on board of the BIOPAN facility extended the list of organisms surviving exposure to space vacuum in LEO with lichens (Sancho et al. 2007) and tardigrades (Jönsson et al. 2008). Both are eukaryotic and multicellular. The macroscopic lichens even survived UV-C exposure during their two-week flight in LEO.

Except for the two free flying satellite missions LDEF and EURECA that were planned to stay in orbit for approximately 1 year and with LDEF accidentally remaining in space for nearly 6 years, exposure of most exobiological experiments in space did not last longer than

**Table 1** Space parameters studied during previous astrobiological experiments in LEO (modified from Horneck 1998)

| Space parameter | SL1[a] D2[a] | LDEF[a] | EURECA[a] | BIOPAN / Foton[a] |
|---|---|---|---|---|
| **Space Vacuum** | | | | |
| Pressure (Pa) | $\approx 10^{-4}$ | $\approx 10^{-6}$ | $\approx 10^{-5}$ | $\approx 10^{-6}$ |
| Residual gas (part $cm^{-3}$) | | | | |
| H | $10^5$ | $\approx 10^5$ | $\approx 10^5$ | $\approx 10^5$ |
| He | $10^6$ | $\approx 10^5$ | $\approx 10^5$ | $\approx 10^5$ |
| N | $10^6$ | $\approx 10^4$ | $\approx 10^4$ | $\approx 10^4$ |
| O | $10^9$ | $\approx 10^5$ | $\approx 10^5$ | $\approx 10^5$ |
| $H_2O$, organics | + | - | - | - |
| $H_2O$ $N_2O$, NO | + | - | + | - |
| **Solar UV radiation** | | | | |
| fluence (J $m^{-2}$) | $\leq 10^3$ | $\approx 10^9$ | $\leq 3x10^8$ | $\approx 10^7$ |
| spectral range (nm) | >110 | >50 | >110 | >110 |
| | >170 | >170 | >170 | >170 |
| | >290 | | >280 | >200 |
| | >300 | | >295 | >280 |
| | 212 | | 220 | >320 |
| | 223 | | 230 | >400 |
| | 230 | | 260 | |
| | 260 | | 290 | |
| | 290 | | | |
| **Cosmic radiation** | | | | |
| dose (mGy) | 0.7 | 4,800 | 200-400 | 82,000[2)] |
| **Temperature (K)** | 243–290 | 264–302 | 295–318 | 235–288 |
| **Exposure time (d)** | 10 | 2,107 | 336 | 10–15 |

[a] Space missions: SL1 (Spacelab 1) with STS 9, Nov. 28 - Dec. 8, 1983; D2 (Spacelab D2) with STS 55, April 26 - May 6, 1993; LDEF (Long Duration Exposure Facility, released with STS 41-C in April 7, 1984 and retrieved by STS-32 in January 20, 1990 and returned to Earth; EURECA (European Retrievable Carrier) released with STS 46 in July 31, 1992 and retrieved with STS 57 in June 24, 1993 and returned to Earth; BIOPAN missions attached to a Foton satellite: BIOPAN 1: June 14 – July 2, 1994; BIOPAN 2: October 9 – 23, 1997; BIOPAN 3: September 9 –24, 1999; BIOPAN 5: May 31 – June 15, 2005; BIOPAN 6: September 14 –26, 2007

[b] depending on shielding, highest values at a mass shielding of 0.017 g $cm^{-2}$, recorded on BIOPAN 1 in 1994. Exposure time (BIOPAN 1 Lid open) 15 days. The peak value of 82 Gy total dose (5.6 Gy per day) was measured behind 17 mg $cm^{-2}$ of shielding mass

approximately 2 weeks (Foton, Spacelab, Gemini). With the availability of the International Space Station (ISS), more extended exposure experiments have become possible. The European Space Agency (ESA) has provided the exposure facility EXPOSE for astrobiology experiments in LEO. We present in this paper the different steps of experiment preparation for EXPOSE, which started with experiment proposals and the selection by peer groups. Studies in the space simulation facilities in order to select suitable specimens, define the ideal exposure conditions and develop the appropriate flight hardware followed as preparation for the launch of EXPOSE to the ISS and the installation outside of the ISS. Valves and lids (only EXPOSE-E) were opened by telecommand (TC), starting the exposure of the EXPOSE samples to the space environment.

## Astrobiological Experiments on EXPOSE

In 1996, ESA issued the first Announcement of Opportunities (AO) for Externally Mounted Payloads for the first Utilisation Phase of the ISS. The following locations for external payloads (Fig. 1) are offered by the fully assembled ISS:

- the Truss segment 3 (S3) of the ISS (USOS Truss Segment and EXPRESS Pallets (Fig. 1A);
- the European Columbus module providing the External Payload Facility (CEPF) with the European Technology Exposure Facility EuTEF (Fig. 1B);
- the Russian module Zvezda providing 2 external attachment points (URM-D-platform) (Fig. 1C); and
- the Japanese Experiment Module providing the Exposed Facility (JEM-EF) (Fig. 1D).

Depending on the location on the ISS, different fields of view are given due to the shading effects by ISS elements and structures. The S3 has four sites (two zenith, two nadir), while CEPF consists of two structures on the starboard cone of the European Columbus module, each for two external payloads. One of the four sites has zenith view, while all others are restricted by their orientation and the ISS structure itself (Wilson 2003).

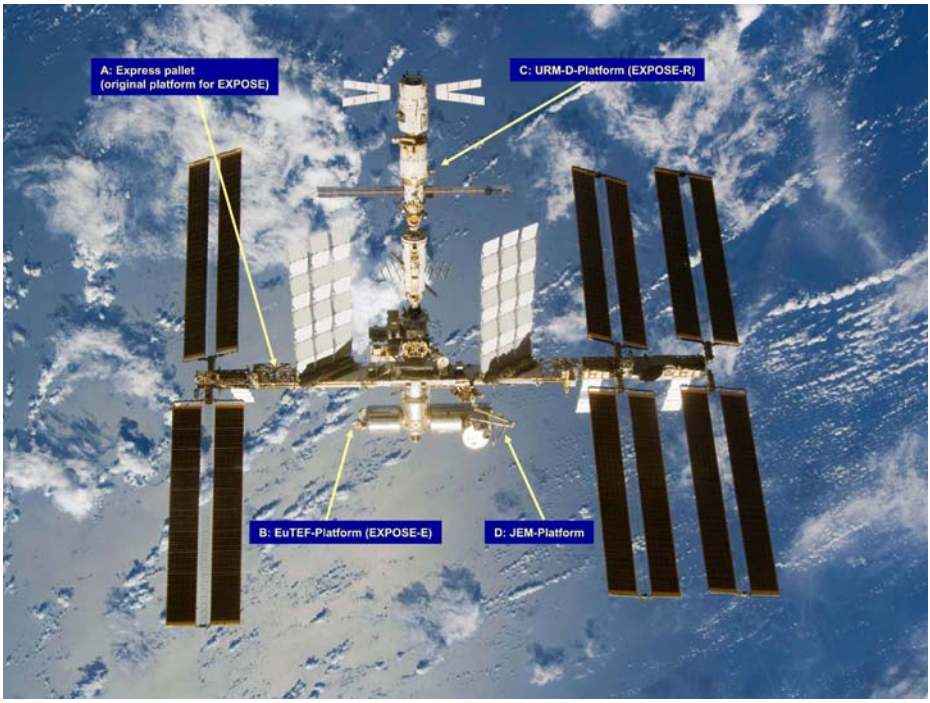


**Fig. 1** Locations for external payloads on the ISS: **A** the USOS Truss Segment and EXPRESS Pallet on the Truss segment 3 (S3); **B** Columbus External Payload Facility (CEPF) with EuTEF and EXPOSE-E; **C** the URM-D-platform at the Russian module Zvezda; **D** the Japanese Experiment Module providing the Exposed Facility (JEM-EF). (Photo credit: NASA, adapted)

## Astrobiological Experiments on EXPOSE-R

In response to ESA's call in 1996 for "Externally mounted payloads for 1st utilization phase" on the International Space Station (ISS), nearly 100 proposals were submitted from different fields of basic research and application, such as technology, space science, life science including exobiology, physical science and Earth observation (Seibert 1998). After peer review and technology feasibility and accommodation study, eight astrobiological experiments were selected. These were targeted either towards

- the understanding of the stability of organic molecules in space in connection with processes of chemical evolution in space (Brack et al. 1999, Cottin et al. 2008), or
- the assessment of the resistance of microbial model systems and biomolecules to the different parameters of space (Horneck et al. 1999) (Table 2).

The latter group consisting of six experiments formed the ROSE (Response of Organisms to Space Environment) consortium under the coordination of DLR. This international ROSE consortium has been composed of scientists from different European

**Table 2** Astrobiology experiments selected after the first call of ESA in 1996 and finally accommodated on EXPOSE-R

| Principal Investigator | Experiment | Topic of research |
|---|---|---|
| H. Cottin (A. Brack[a]) LISA-Créteil (France) | AMINO | To study photochemical processing of amino acids and samples relevant to cometary and Titan chemistry |
| P. Ehrenfreund Leiden Observatory (NL) | ORGANIC | To study the evolution of organic matter in space |
| C. Cockell (D. Wynn-Williams[a]) Open University(UK) | ROSE-1/ENDO | To assess the impact of extraterrestrial UV radiation on microbial primary producers (algae, cyanobacteria) |
| R. Mancinelli Seti Institute, NASA Ames (USA) | ROSE-2/OSMO | To assess the protective effects of osmophilic microorganisms enclosed within gypsum-halite crusts |
| G. Horneck DLR (Germany) | ROSE-3/SPORES | |
| with R3D | To assess the protection of spores by meteorite material against space conditions: UV, vacuum and ionising radiation/ Radiation dosimetry | |
| J. Cadet C.E.A. Grenoble (France) | ROSE-4/PHOTO | To determine the photoproducts resulting from exposure of dry DNA samples or bacterial spores to solar UV radiation |
| N. Munakata University of Tokyo (Japan) | ROSE-5/SUBTIL | To determine the mutational spectra of *Bacillus subtilis* spores induced by space vacuum and/or solar UV radiation |
| G. Rontó Research Lab. for Biophysics, Budapest (Hungary) | ROSE-8/PUR | To determine the biologically effective dose of solar extraterrestrial UV radiation by biological dosimetry |

[a] Initially proposing scientist

countries, from USA and from Japan. In the following years, the flight hardware, i.e. the EXPOSE-facility, was designed by ESA in close consultation with the different astrobiology science teams.

A dedicated Experiment Verification Test Program for the EXPOSE experiments (EXPOSE-EVT) was established (C. Panitz, in preparation) and supported by ESA in order to achieve the necessary flight readiness of the experiments and — at the same time — use the results of the tests as feed back into the hardware design process. It included activities as follows:

- assessment of the desiccation and UV radiation resistance of the different species of ROSE in order to select suitable organisms for the flight;
- determination of the acceptable temperature ranges;
- assessment of the biocompatibility of the different samples and materials;
- selection of analytical methods for the different biological endpoints to be investigated;
- tests of sample preparation techniques for the space experiment;
- measurement of UV-dose effect relationship for different polychromatic spectral ranges in order to choose suitable filter combinations for the flight unit;
- definition of the optical requirements and
- optimization of analytical methods for the different biological endpoints adapted to the small sample volumes required by the space hardware.

The EVTs were performed within the Planetary and Space Simulation Facilities (Ψ PSIs) at DLR and have provided an in-depth understanding of the responses of the different test systems to selected simulated space parameters (Douki and Cadet 2003, Fekete et al. 2004, 2005, Rontó et al. 2004, Hegedüs et al. 2006, Moeller et al. 2007).

Because the initially planned site for the installation of the EXPOSE facility, the EXPRESS Pallet of the ISS, was not provided in time, ESA finally selected as alternative solution the URM-D platform on the Russian Zvezda module of the ISS (Fig. 1) as attachment site of the EXPOSE-facility. Without changing the original structure and sample exposure design, the EXPOSE concept was adapted for accommodation on the URM-D platform and the facility now called EXPOSE-R was developed. In the course of negotiations on the EXPOSE-R mission on Zvezda, a set of Russian biological samples provided by the Institute of Biomedical Problems (IMBP) was added to the experiments on EXPOSE-R. This included bacterial spores, fungal spores, plant seeds, and eggs of lower crustacean and cryptobiotic larvae. Passive dosimeters for ionizing radiation measurement and the active radiation measuring instrument R3D complemented the chemical and biological experiments. EXPOSE-R was successfully launched to the ISS on November 26, 2008 from Baikonur on board of a Progress capsule (http://www.esa.int/esaHS/SEMAVT9WYNF_index_0.html).

## Astrobiological Experiments on EXPOSE-E

As an alternative solution for the original flight module of EXPOSE, ESA decided to move EXPOSE to the European Technology Exposure Facility (EuTEF), one of the four CEPF on Columbus (Fig. 1), together with eight other external instruments. The hardware of EXPOSE, now called EXPOSE-E, was adapted for accommodation on a bracket on the EuTEF platform, providing Zenith orientation of the samples. ESA issued another AO in 2004 for a second batch of exposure experiments to be performed in space. The astrobiological experiments selected after peer review for flight on EXPOSE-E are listed in Table 3. They are performed by international groups of scientists and are intended to

**Table 3** Astrobiology experiments selected after the second call of ESA in 2004 and finally accommodated on EXPOSE-E

| Principal Investigator | Experiment | Topic of research |
|---|---|---|
| G. Horneck DLR (Germany) | PROTECT | To determine the resistance of spacecraft isolates to outer space for planetary protection purposes |
| D. Tepfer CNRS, Versailles (France) | SEEDS | To test plant seed as a terrestrial model for a Panspermia vehicle and as a source of universal UV screens |
| H. Cottin LISA-Crétail (France) | PROCESS | To study photochemical organic chemistry relevant to comets, meteorites, Mars and Titan |
| P. Rettberg DLR (Germany) | ADAPT | To study molecular adaptation strategies of microorganisms to different space and planetary UV climate conditions |
| S. Onofri Università degli studi della Tuscia di Viterbo (Italy) | LIFE | To study the resistance of lichens and lithic fungi at space conditions |
| D-P. Häder University of Erlangen (Germany) | R3D-2 | Active radiation dosimetry (VIS, UV-A, UV-B, UV-C; LET spectra of cosmic radiation) |
| G. Reitz DLR (Germany) / F. Vanhavere SCK CEN (Belgium) | DOSIS/ DOBIES | Passive radiation dosimetry at the sample sites |

investigate the effects of space conditions on organic chemical compounds (Cottin et al. 2008) and on microorganisms (bacterial spores, extremophiles including lichens and fungi), plant seeds and microbial endolithic communities in their natural habitat. Upon request of the Principal Investigators, during an Experimenter Working Group Meeting in February 2006 at ESA, dosimeters for cosmic ionizing radiation and solar UV radiation were added to EXPOSE-E (Table 3). The dosimetric systems were derived from experiments on EXPOSE-R (ROSE 3 experiment SPORES — Spores in artificial meteorites) as well as from BIOPAN experiments on the FOTON satellite (Reitz et al. 2002, Sancho et al. 2007, Pálfalvi et al. 2007, 2008, Fehér and Pálfalvi 2008, Damasso et al. 2009).

## Astrobiological Relevance of the Experiments on EXPOSE-E and EXPOSE-R

With the experiments onboard of the EXPOSE facilities various aspects of astrobiology are investigated that cannot be sufficiently approached by use of laboratory facilities on ground (Table 2 and 3). The chemical set of experiments is designed to reach a better understanding of the role of interstellar, cometary and planetary chemistry in the origin of life (Brack et al. 1999, Cottin et al. 2008). Comets and meteorites are interpreted as exogenous sources of prebiotic molecules on the early Earth. From studies on the chemical evolution, survival, destruction and modification of complex organics, e.g., PAHs, fullerenes and complex aromatic networks in outer space experimental clues will be obtained on the photochemistry of these compounds in the interstellar and interplanetary medium. Data obtained from the studies on complex organics of cometary interest will support the interpretation of the future in-situ data, to be obtained from the Rosetta mission after landing on Comet 67P/Churyumov-Gerasimenko in 2014 (ESA 2008). Finally the chemical experiments will contribute to the understanding of the chemical processes on Saturn's moon Titan and possible analogies to the prebiotic chemistry on the early Earth (Raulin 2007).

The biology experiments use the full extraterrestrial spectrum of solar UV radiation and suitable cut-off filters to study both, the role of the ozone layer in protecting our biosphere and the likelihood of resistant terrestrial microorganisms and microbial communities to survive in outer space. The latter studies will provide experimental data to the hypothesis of lithopanspermia (Nicholson 2009), i.e. the interplanetary transfer of life via meteorites, and they will provide basic data to planetary protection issues, i.e. the need to prevent contamination of target planets, e.g. Mars by terrestrial microorganisms (Horneck et al. 2007). To get better insight into the habitability of Mars, one set of samples will be exposed to simulated Martian conditions (UV-radiation climate, pressure, atmosphere), with and without a protective cover of simulated Martian regolith. The biological test samples selected are hardy representatives of bacteria, Archaea, lichens, fungi and plant seeds, i.e. of various branches of life, also in their natural communities. Most types have already demonstrated their resistance to outer space during short term missions, e.g. on board of the ESA BIOPAN facility (Horneck et al. 2001, Rettberg et al. 2004, Sancho et al. 2007)

In summary, all data achieved from the astrobiological experiments on both EXPOSE missions will add to our understanding of the origin and evolution of life on Earth and on the possibility of its distribution in space or origin elsewhere.

## Development of EXPOSE Flight Hardware

Following the ESA AO in 1996 and the final selection of experiments, four payloads for external pallets were developed by ESA (Seibert 1998; Wilson 2003): a Technology Exposure Facility (TEF), Solar Packages with three experiments on a coarse pointing device, an Atomic Clock experiment (ACES) and a Space Exposure Biological Assembly (SEBA) to accommodate the EXPOSE facility for the astrobiology experiments (Table 2) and the MATROSHKA facility, a human phantom to determine the depth dose distribution in astronauts during Extra Vehicular Activity (EVA) (Reitz and Berger 2006, Reitz et al. 2009). SEBA with EXPOSE and MATROSHKA was foreseen to be accommodated on a zenith oriented pallet of the ISS Truss structure via the EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Pallet concept to be provided by Brazil (NASA 1999) (Fig. 1). EXPRESS Pallets would allow installation and exchange of individual experiments by EVA. A central Standard Payload Computer and a Power Distribution Unit to support the two independent experiment units EXPOSE and MATROSHKA were planned as part of SEBA. To obtain defined irradiances of solar UV, which requires vertical insolation of the samples, EXPOSE should be mounted on a dedicated sun pointing device. A lid system was designed for remote control that provided insolation of the samples during the sun-pointing phases only. SEBA was scheduled to be installed on the ISS in 2001. However, the EXPRESS Pallet was not provided in time, and finally a decision was made to move EXPOSE to the European Technology Exposure Facility (EuTEF), one of the four CEPF on Columbus (Fig. 1). An adapter bracket was designed to allow zenith orientation of the EXPOSE samples, but without sun pointing ability. When the delivery of the Columbus module with its four external platforms was delayed too, a timely access to ISS for EXPOSE and its astrobiological experiments seemed to be possible only by a Russian carrier to the URM-D platform on the Russian Zvezda module. At the end, 2 EXPOSE facilities were provided by ESA: one, EXPOSE-R to be installed at the URM-D platform of Zvezda, and a second

unit, EXPOSE-E, the original flight unit, as part of EuTEF. In both cases, the lids were deemed no longer necessary, because of lack of a sun-pointing device. While EXPOSE-E construction and tests were already too advanced for any changes, lids were consequently removed from the EXPOSE-R core instrument. In addition, the trays of EXPOSE-R were designed to be exchanged in flight by EVA, while the completely loaded EXPOSE-E facility will be returned together with EuTEF by the Space Shuttle after completion of the mission.

The astrobiological experiments selected (Table 2 and 3) required a multi-user unit designed to accommodate a variety of biological and chemical samples. Though all samples required access to space conditions, above all space vacuum and/or solar UV radiation, individual samples needed defined exposure conditions: different optical filters for wavelength selection and/or attenuation of solar UV radiation, as well as sample carriers specifically adapted to the sample requirements. For this, the EXPOSE facility was designed and developed by the payload developer Kayser-Threde, Munich, Germany, based on the heredity of previous exobiological exposure devices, flown on Spacelab, EURECA and BIOPAN/Foton missions (Demets et al. 2005, Baglioni et al. 2007) and in close consultation with the Principal Investigators. EXPOSE has a box-shaped core structure providing heating systems, temperature and UV sensors and systems for ground telemetry, communication and commanding. Three sample trays, each with four square sample compartments of approximately 77×77 mm² inner widths and 36 mm inner depth are mounted in parallel on top of the core structure (Fig. 2). To allow access to space vacuum, some compartments of each tray are connected by a venting line to a common valve which is remotely operated by telecommand (TC). In space, these valves of the trays are opened by TC. Other compartments, which contain a defined atmosphere (e.g. simulated Martian atmosphere) or which harbor control samples kept at atmospheric pressure in inert gas (e.g. argon), are disconnected from the venting line and hermetically sealed to maintain the pressure and composition of the inner gas provided during closure of the compartment or tray.

The samples are accommodated in at least two layers of sample carriers (one top carrier for UV exposure of the samples and one or two carrier(s) below hosting the dark control samples) that are integrated into the compartments (Fig. 3). Depending on the type of carrier, up to 64 samples are accommodated in one carrier. Each compartment is covered by an optical filter frame carrying long-pass filters for wavelength selection (> 110 nm,>200 nm) as well as neutral density filters of different transmissions (100%, 1%, 0.1%, 0.01%, 0.0001%). The compartments of the ROSE experiments in EXPOSE-R (Table 2) and of the biological experiments in EXPOSE-E except SEEDS (Table 3) are additionally covered by 8 mm thick $MgF_2$ or quartz (Suprasil) windows. A maximum of sixteen different combinations of optical neutral density filters and long-pass filters are possible for each compartment to modulate the incident UV intensity and wavelength range.

The core structure of each EXPOSE facility provides common functionalities and services: a control unit for lid-motors (only in EXPOSE-E, where the lids are part of the thermal control system and closed if the temperature rises above the upper acceptable temperature limit for the samples of 53°C) and valves, data acquisition, four UV-B sensors located at the four corners of the facility, one radiometer, a thermal control system based on two independent heater circuits, multilayer insulators, coatings, an electrical interface to the EuTEF / URM-D data handling and power unit and the mechanical interface to EuTEF / URM-D. The EXPOSE actuators are controlled by software via the experiment control unit

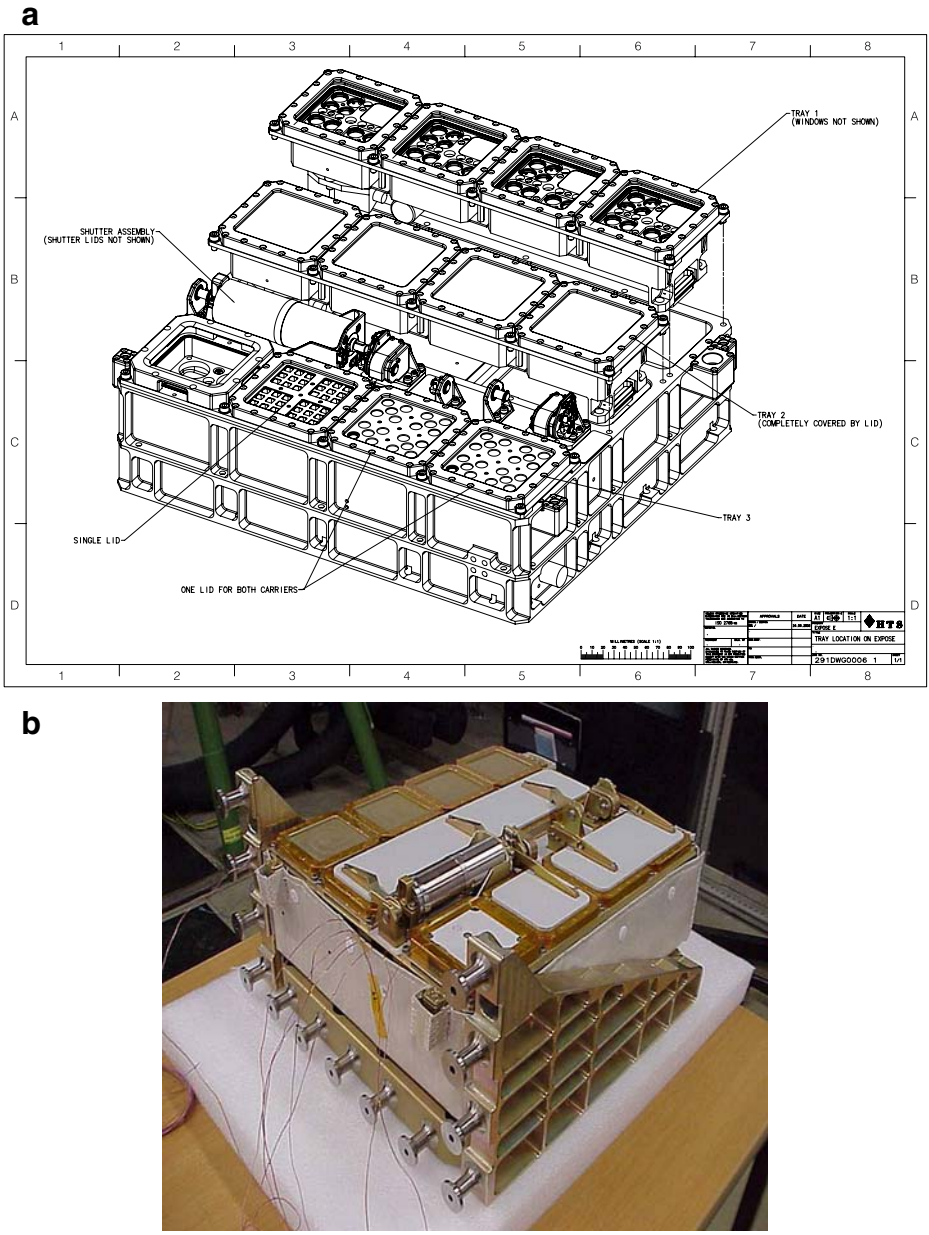


**Fig 2** EXPOSE facility, Scheme of EXPOSE core device and trays (Kayser-Threde) **a** and Photo of EXPOSE-E, already mounted to the EuTEF adapter bracket **b** (credit: ESA and KT)

microcontroller, also operable via telemetry / telecommand link. The micro-controller takes care of

- acquisition and transmission of housekeeping data, data from temperature and solar sensors and science data from R3D, data storage in case of data link interruption,

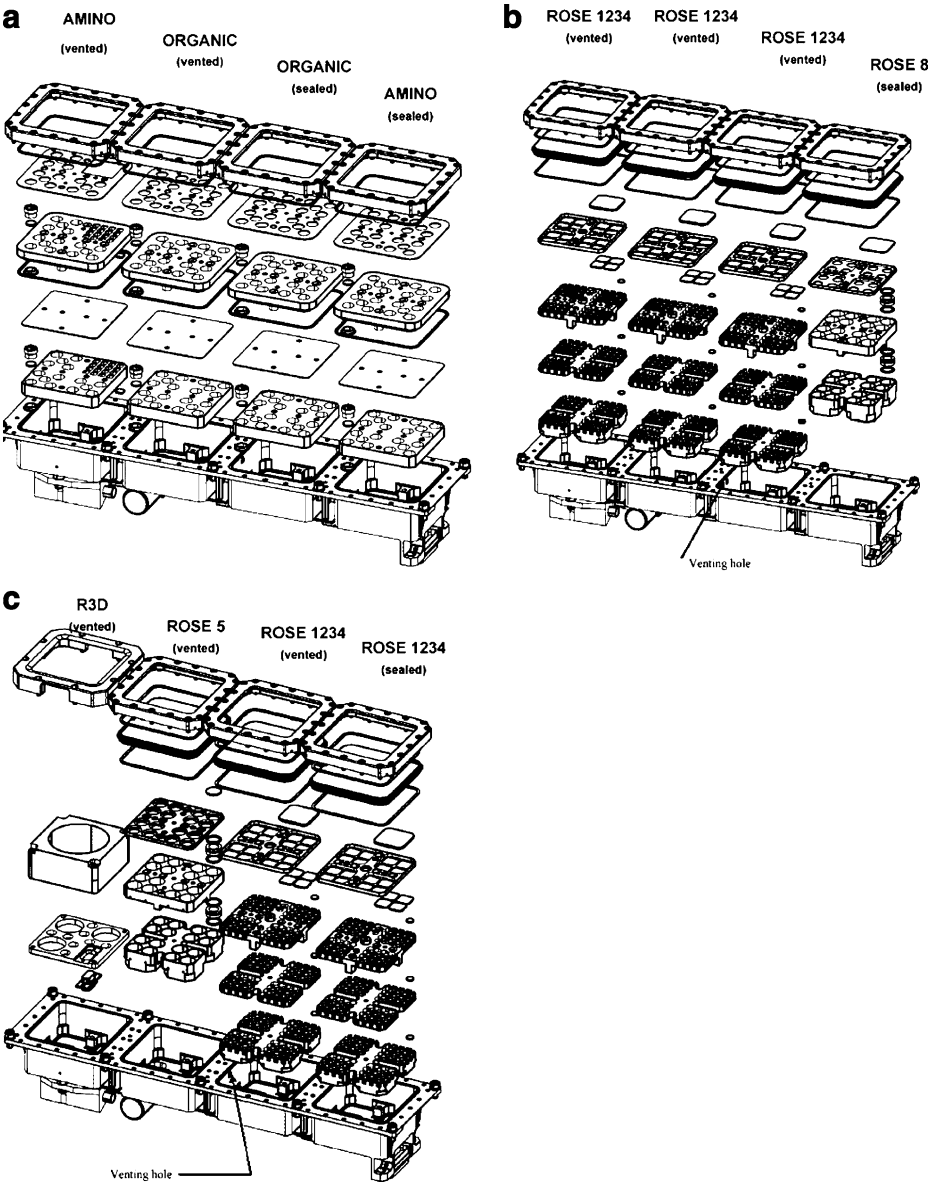


**Fig. 3** Arrangement of the subunits of the 3 trays of EXPOSE-R (see also Table 2) according to the different experiment requirements; **a** Tray 1 for the experiments AMINO and ORGANIC including SEEDS and the IBMP samples; **b** Tray 2 for the experiments ROSE 1, 2, 3, 4, 8 and IBMP samples; **c** Tray 3 for the experiments ROSE 1, 2, 3, 4, 5 and R3D (Courtesy: ESA)

- command and control of the three motor-driven lids by stepper motors (EXPOSE-E only), three motor driven valves for venting of experiment compartments,
- thermal control of experiments and facility with two different sets of thermostat controlled heaters accommodated underneath each experiment tray and on the inner side of the facility frame and

- overheat protection by automatic closure of lids, when temperature exceeds 53°C (EXPOSE-E only), and additional power shut down, when temperature rises above 58°C to prevent further heating by the electronics.

Environmental data from six temperature sensors attached to the three trays, four UV-B sensors and one radiometer are available every 10 seconds, in addition to those on health, valve and lid status of EXPOSE.

## Flight Mission Protocol

### EXPOSE-E Flight Preparation

EXPOSE-E was scheduled to be launched to the ISS together with the European Columbus module and its external EuTEF platform in December 2007 (Space Shuttle flight STS 122). The individual samples of the experiments (Table 3) were prepared in the laboratories of the Principal Investigators and transported to DLR for integration into the trays of EXPOSE-E. Two sets of samples were provided: one set for the flight experiment and one set to be accommodated in an identical set of trays for the mission ground reference experiment. The latter trays are used to follow the environmental data of the flight unit (e.g. temperature profile, vacuum exposure, UV radiation) using the Ψ PSI facilities at DLR.

After assembly, two trays of EXPOSE-E (tray 1 and 3) were filled with nitrogen at ambient pressure and closed. They were evacuated after installation outside of the Columbus facility at the beginning of the mission, thereby exposing all samples in those two trays to the space vacuum of LEO; $MgF_2$ windows allow transmission of short wavelength solar UV. The third tray (tray 2) was designed to provide a simulated Martian climate (atmosphere, pressure, UV radiation spectrum). After sample integration it was filled with a simulated Martian atmospheric gas with a final pressure inside the tray of $10^3$ Pa and composed of 1.6% Argon, 0.15% Oxygen and 2.7% Nitrogen in $CO_2$ and hermetically closed. To simulate the Martian UV radiation climate, long-pass filters cutting off wavelengths <200 nm were used. All samples in this tray are determined to remain in this simulated Mars atmosphere for the whole mission. To prevent an accidental opening of the valve during mission operation, this function was inhibited for telemetry of EXPOSE-E. A final functionality test of R3D, the only active experiment on EXPOSE-E, proved full functionality and correct integration of the instrument.

On July 19, 2007, the three trays ready for transportation to Kennedy Space Center (KSC) were presented to ESA and shipment release was granted. At KSC, the EXPOSE-E core facility was already installed on the EuTEF platform and tested. The three trays were integrated and the complete EuTEF platform (Fig. 4) was installed into the Cargo bay of STS-122, Space Shuttle Atlantis, together with the SOLAR platform next to the Columbus module, at launch pad 39A.

### EXPOSE-E Mission

Launch of EXPOSE-E was scheduled for December 6, 2007 with STS-122. A problem with two Engine Cut Off sensors led to a postponement of the launch. Launch date was finally set to February 7, 2008 and Atlantis took off from KSC at 07:45 p.m. GMT. On February 15, 2008, during the third EVA of the STS-122 mission, EuTEF including EXPOSE-E was successfully installed on the starboard cone of the Columbus module (Fig. 5). Two days later, on February 17, 2008 at 03:10:30 GMT, the EXPOSE-E Facility Support Center of

**Fig. 4** EXPOSE-E facility mounted on the EuTEF platform during pre-flight tests on ground (courtesy Ralf von Heise-Rotenburg, KT)


**Fig. 5** EXPOSE-E after being installed on the EuTEF platform at the balcony of the European Columbus module of the ISS in February 2008, before commissioning and opening of the lids (credit ESA and NASA), see also (http://www.go.dlr.de/musc/expose/)

the Microgravity User Support Center (MUSC) at DLR in Germany contacted EXPOSE-E via telemetry during check out.

On February 20, 2008, at 08:28:15 GMT, MUSC at DLR commanded EXPOSE-E through the commissioning phase, opening the valves of trays 1 and 3, opening all three lids and activating R3D. The status of EXPOSE-E was nominal except for one pressure sensor of tray 3, indicating no pressure decrease in that tray. Because two sensors at the valve of tray 3 confirmed the open status of the valve, its pressure sensor was assumed to show a malfunction. Housekeeping temperature data from the six temperature sensors and UV data from the four UV sensors and the radiometer as well as science data form R3D were down-linked successfully. Nearly 15 years after the ERA Mission on EURECA, a new long term astrobiological exposure experiment was successfully launched and is operational in space for at least 1.5 years, exposing more than 470 individual samples to selected space conditions. The retrieval of EXPOSE-E with the whole EuTEF platform is currently scheduled for August 2009 with Shuttle flight STS 128 – 17A.

## EXPOSE-R Flight Preparation

Launch of EXPOSE-R to the ISS was scheduled for November 2008 from Baikonur with a Progress module. As for EXPOSE-E, for the astrobiology experiments (Table 2) two sets of samples were prepared by the Principal Investigators in their laboratories, and then transported to the DLR for integration into the trays. More than 1200 samples were accommodated in the EXPOSE-R flight unit (Fig. 3) as well as in the ground control unit. The compartments were closed in an argon atmosphere, capturing the inert gas at atmospheric pressure inside the trays. It has been shown in previous experiments and during the EVTs that during storage argon as well as nitrogen are less aggressive to the samples than air, probably by preventing oxidative damage. The completely equipped and closed trays of the flight unit were handed over to ESA and Kayser-Threde on August 14, 2008 for integration into the EXPOSE-R core facility. After integration into the core facility and final testing, the complete EXPOSE-R was transported to its launch destination Baikonur on October 25, 2008.

## EXPOSE-R Mission

EXPOSE-R was launched successfully as scheduled on November 26, 2008, 12:38 GMT, with Progress 31-P. After docking with the ISS on November 30, EXPOSE-R was transferred from the Progress capsule into the Russian Zvezda module. During the preparation of EXPOSE-R for external installation, the bolt of tray 2, which is required for later exchange of the tray, broke. The problem was resolved by fastening tray 2 in a different way using screws available on board of the ISS. Hence, the installation of EXPOSE-R on the URM-D platform of Zvezda started as scheduled during the EVA on December 23, 2008. EXPOSE-R was successfully attached to the external platform by the Russian Flight Engineer Yury V. Lonchakov and the NASA Commander E. Michael Fincke during this EVA (Fig. 6). However a failure in the power connection led to the decision to return EXPOSE-R back into the Zvezda module of the ISS. The power failure was only understood and resolved when the EVA was over. EXPOSE-R had to wait for the next EVA on March 10, 2009, to be installed on the URM-D platform. In the meantime, the broken bolt of tray 2 was exchanged. During the March 2009 EVA performed by the same two astronauts, successful power and data connection was monitored online at MUSC, DLR, and telemetry on health and valve status received. Starting March 11, 16:43 GMT, the


**Fig. 6** EXPOSE-R temporarily attached to the URM-D platform of the Russian module Zvezda on 23 December 2008, with protecting cover (Credit: ESA and NASA)

opening of the 3 valves in 2 minute time steps by telecommand was followed on ground. EXPOSE-R and its more than 1,000 samples have gone operational.

After the planned 1 to 1.5 year mission, each of the three trays of EXPOSE-R will be removed from the core facility and returned to Earth by a Soyuz module, leaving the EXPOSE-R core facility on the URM-D platform in prospect of reloading with a new set of trays with a new set of astrobiological experiments.

## Discussion and Conclusions

The EXPOSE facilities accommodate more than 470 (EXPOSE-E) and 1,200 (EXPOSE-R) samples from 8 international scientific groups each. For both facilities, Experiment Verification Tests (EVTs) proved necessary and helpful to successfully customize the hardware and the requirements of the experiments. The biological and chemical samples varied in their demands on the interfaces to the EXPOSE facilities, especially the sample carriers. Sample fixation and accommodation strategies were verified and fit checks performed. In addition biocompatibility of the samples with each other and the materials of the facility was tested. Pre-flight tests with candidate samples under simulated space parameters were performed. They are the *conditio sine qua non* to allow selection of the best suited samples and to increase the scientific outcome of the post-flight analysis and its interpretation (Onofri et al. 2008).

Therefore, extensive Experiment Verification Tests (EVTs) are necessary for a successful and scientific valuable space experiment. One requisite for successful pre-flight EVTs, besides space conditions simulating facilities, is the availability of the flight identical hardware. Only the timely availability of hardware for tests allows a straight-forward adaptation of the final hardware with respect to the samples carriers and their biocompatibility. For EXPOSE-E and EXPOSE-R, a complete additional set of hardware for the ground controls was provided by ESA. These sets are now used for the parallel Mission Ground Reference Experiment, which runs in the Planetary and Space Simulation Facilities at DLR. For early EVTs the EXPOSE hardware was not yet available. In those cases, the hardware of past missions, e.g. EURECA, was used. Likewise important for a careful preparation of the flight experiments is the pre-flight performance of Experiment Sequence Tests (ESTs) that rehearses the final call for and provision of flight and ground samples, the final accommodation procedures and proves equally important for a successful logistics and integration of a high number of samples of several international groups. With

both EXPOSE facilities being successfully in space, extensive pre-flight test programs were performed, which increase the chances for a successful study of the biological responses and chemical processes under real space conditions.

Future exposure facilities for astrobiology experiments could be further improved. In most cases, astrobiology experiments try to simulate as much as possible the conditions experienced by organic chemical and biological matters when traveling with comets or asteroids or when being exposed to extra-terrestrial conditions. In this case, low temperatures, far below 0°C, are desired, whilst maintaining a full exposure to solar UV radiation. This explains why a future evolution of a facility like EXPOSE should be provided with some cooling devices, either passive, like heat pipes and radiators conductively linked to the experiment trays, or semi-active, like thermoelectric junctions (Peltier) linked to heat exchangers. In addition, sun pointing devices and sample compartments with embedded temperature sensors should be part of future development, as well as active and passive dosimetric systems for UV, visible light and ionizing radiation, able to also determine the angular position of the sun. A pressure measurement system, providing real-time in flight environmental data via telemetry, is of interest for the scientists and for mission parallel ground based simulations.

EXPOSE-type facilities might be used in the near future as "test-bed" for experiments in support of upcoming planetary exploration missions. The design and development of the mobile astrobiology package Pasteur to be operated on the Martian surface during the ExoMars mission (Vago and Kminek 2007), will most probably require testing of materials, electronic components and mechanical devices that will have to be operated continuously when exposed for long time to extraterrestrial conditions (low pressure or vacuum, large temperature variations, high radiation, electric and magnetic fields, etc.). Similar tests will also become necessary for any future long term operation on the Moon.

Looking at the near term plans of ESA for Mars exploration, it is clear that the first missions (ExoMars Pasteur, Mars Sample Return) shall bring to the Martian surface a set of instrumentation. Their bioload needs to be controlled and reduced according to the COSPAR Planetary Protection Guidelines (http://cosparhq.cnes.fr/Scistr/PPPolicy(20-July-08).pdf), i.e. resulting in a reduction of living terrestrial microorganisms, and cleaned from Earth-organic agents, in the attempt to avoid contamination when measuring and investigating the Martian regolith and rock characteristics. These planetary protection issues are at the moment being investigated, e.g. in the experiments PROTECT and ADAPT on board of EXPOSE-E (Table 3). Similar studies should be fostered, because exposure platforms like EXPOSE might be useful for validation, qualification and testing of materials or technical devices in preparation of missions to Moon or Mars.

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