The ESA Laboratory Support Equipment for the ISS

A. Petrivelli
Laboratory Support Equipment Section, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

The Laboratory Support Equipment (LSE) for the International Space Station (ISS) is a suite of general-purpose items that will be available onboard the Station either as self-standing facilities or as equipment that can be used at defined locations. Dedicated to supporting system maintenance and payload operations, some LSE items are derived from commercial equipment, while others have been specifically developed for the ISS.

ESA is currently engaged in developing three pressurised facilities and one pointing mechanism that will become part of the LSE complement, namely:
- **the Minus Eighty degree centigrade Laboratory Freezer for the ISS (MELFI)**
- **the Microgravity Science Glovebox (MSG)**
- **the cryogenic storage and quick/snap freezer system (Cryosystem)**
- **the external-payload pointing system (Hexapod).**

Introduction

The LSE programme was started at ESA in 1994 following the finalisation of the Agreement in Principle for ISS Early Utilisation, which was subsequently translated into a Memorandum of Understanding (MOU) in 1997. According to this Agreement, NASA provides ESA with flight opportunities and resources for accessing the ISS before the ESA Columbus module is launched. In exchange, ESA provides NASA with goods and services. This includes the development and delivery of the two pressurised facilities – MELFI and MSG – and the external payload pointing mechanism – Hexapod.

Later, the LSE programme was extended to include the development of another pressurised facility – the Cryosystem – as well as the sustaining engineering for MELFI, MSG and Cryosystem. Those additional items were introduced with the ESA/NASA Arrangement for the Columbus Laboratory Launch, signed in 1997. In the same year, an MOU was signed between ESA and NASDA whereby NASDA provides ESA with twelve ISS Standard Payload Racks (ISPR). In return, ESA provides NASDA with a MELFI unit, identical to those to be delivered to NASA.

In addition, the LSE programme includes the development of general payload Ground Support Equipment (GSE), such as the Test Equipment for Payload Development (TEPAD), originally developed for supporting the LSE facilities, but now available as ISS interface simulators for the development of any pressurised payload (Fig. 1).

From 1994 onwards, the LSE programme established and has maintained programmatic and technical interfaces with the NASA ISS Payload Office and the NASDA Payload Organization, as well as with the NASA centres responsible for the various disciplines, which include Marshall Space Center (MSFC) Microgravity Program Office, the Johnson Space Center (JSC) Environmental Control Department, the Ames Research Center (ARC) Life Science Program Office, and the Langley

Research Center (LaRC) Earth Observation Missions Office.

As result of this activity, Joint Implementation Plans for all the projects have been established and put under the control of the Multi-lateral Payload Control Board (MPCB).

The LSE development programme

The four LSE projects are currently at different stages of implementation:

- MELFI and MSG have completed their design and development phases. MSG was delivered to NASA in October, and MELFI will be shipped in March 2002.
- Hexapod is in the final stages of development, with delivery to NASA foreseen for mid-2002.
- Cryosystem has been undergoing basic scientific and utilisation requirement assessments, before starting the preliminary design phase (Phase-B) at the beginning of February.

The same general development philosophy has been adopted for the first three projects. The Phase-B, which lasted about two years, has included the development of breadboards of the most critical equipment and assemblies and has demonstrated basic functional performance. The main development phase (Phase-C/D) was started in October 1996 for MELFI and MSG, and in January 1998 for Hexapod.

Many technical challenges have been encountered during the development of the first three payloads:

- they were among the very first to be designed for the ISS, for an environment and payload infrastructure that were not yet settled
- the ten-year-lifetime and in-orbit-maintenance design requirements for the two pressurised facilities were important novelties, and the design was heavily driven by those requirements
- the MELFI development included a significant effort for the preparation of the two key technologies on which the freezer's design was based, namely the Brayton turbo-compressor cooler and the super-vacuum thermal insulation; significant breadboarding and qualification effort was accomplished without exceeding the restricted financing available
- the MSG, as the first user of the European Standard Payload Outfitting Equipment (SPOE), had to adjust to the contemporary development of those items and at the same time serve as the test bed for their development
- the not yet settled ISS environment for the external payload rendered the development of the Hexapod external interfaces both difficult and risky; only the good technical coordination between the NASA and ESA project teams has allowed progress to be made in the development activities.

Ground models have been produced for MELFI and MSG to support the science-procedure preparation and crew-training activities. In addition, engineering models for each facility have supported the development activities and will be available for the sustaining engineering during the operational phase. With the design and development of MELFI and MSG, the rack structural design and qualification expertise for the NASDA-provided ISPR has been fully acquired by ESA.

Following the Memorandum of Understanding, NASA will assume ownership of the LSE payloads and will be responsible for their operation, but ESA will have to provide spares and technical support for their maintenance. These activities will be part of the ESA Exploitation Programme, once it is initiated and operational. Due to the time constraints, however, the detailed responsibilities and activities to be performed within the scope of the general LSE programme agreements have already had to be defined and agreed with NASA. After many meetings and discussions, it has been possible to baseline Logistic Support Plans for MELFI, MSG and Cryosystem, which have been accepted by all parties.

Conclusions

Within the ESA LSE programme, the MSG is now integrated into the MPLM ready for an expected launch by May 2002. The MELFI and Hexapod activities will soon be completed in Europe and these items delivered to NASA. The Cryosystem is entering the design phase.

Significant experience has been accumulated with these projects, not least in coping with the many challenges generated by the Inter-Agency Barter Agreement environment in which they are taking place. So far, all of the technical objectives for the individual facilities have been met within the assigned programmatic constraints. This allows us to conclude that the ESA LSE programme has demonstrated the usefulness and practicality of the Inter-Agency Agreements, whereby the participating agencies exchange goods and services without a direct exchange of funds. They have allowed optimal exploitation of the resources available at the various Agencies. Some hard lessons have also been learned, in that the mechanism only works well if the basic requirements – technical and programmatic – and the procedures for handling changes, which are unavoidable when dealing with long-duration projects, are firmly established together with the initial political agreements.

MELFI

J.A. Jiménez
Laboratory Support Equipment Section, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

A. Brunschvig
Astrium Space, Toulouse, France

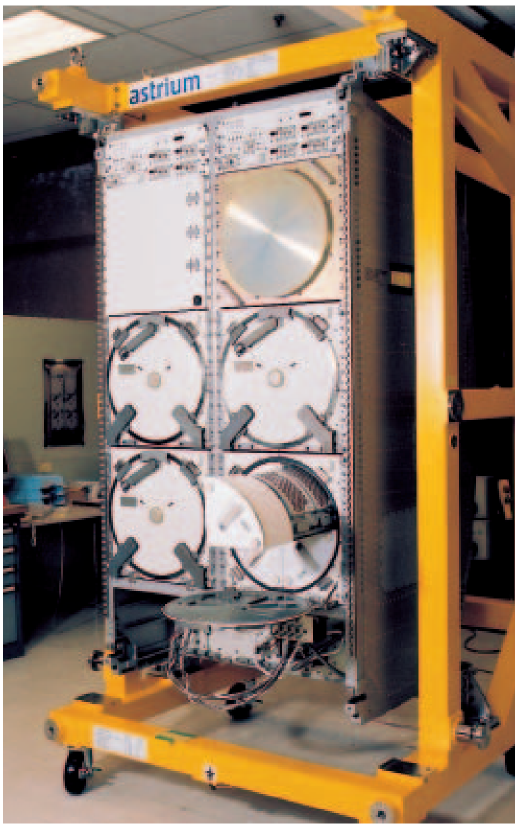
Introduction

The Minus Eighty degree celsius Laboratory Freezer for ISS (MELFI) is a rack-sized facility that will provide the Space Station with a refrigerated volume for the storage and fast freezing of life-science and biological samples (Fig. 1a,b). It will also ensure the safe transportation of conditioned specimens to and from the ISS by flying in fully powered mode in the Multi-Purpose Logistic Module (MPLM) installed in the Shuttle's cargo bay. Continuous operation for up to 24 months is foreseen for each MELFI mission.

MELFI has been developed by the Agency under various Barter Agreements, whereby ESA will deliver three MELFI flight units to NASA and one flight unit to NASDA. In addition, ESA has agreed to deliver certain ground units to NASA and to provide the necessary spares and sustaining engineering to maintain them for up to 10 years of operations.

ESA selected Astrium-Toulouse (formerly Matra Marconi Space) as its prime contractor; the other main sub-contractors participating in the MELFI industrial consortium are:
– Air Liquide (F), for the Brayton subsystem
– Linde AG (D), for the MELFI cold chain
– Kayser-Threde (D), for the electrical subsystem and some rack components
– ETEL (CH), for the motor and motor-drive electronics
– DAMEC (DK), for the utilisation hardware and concept.

After a pre-development Phase-B study, the main development phase (Phase-C/D) began in January 1997. The Preliminary Design Review (PDR) was completed by the end of that year, and the Critical Design Review (CDR) was successfully completed in summer 1999. Staggered verification reviews were completed by February 2002. The Qualification/Acceptance



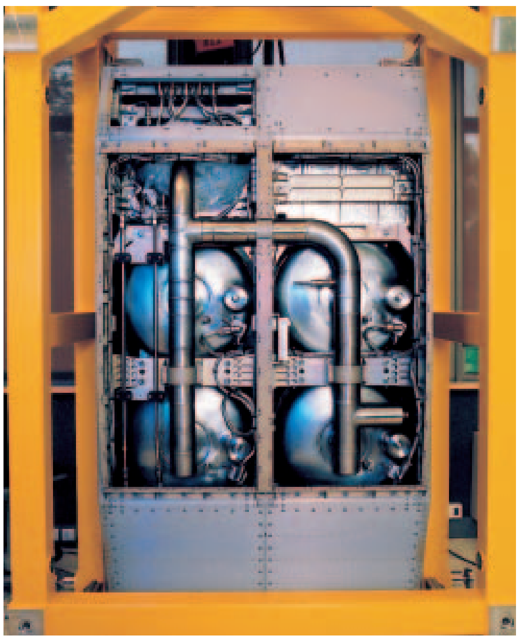


Figure 1. (a) MELFI first flight unit with one dewar door open and a tray partially extracted, and (b) rear of the unit with the cover removed to show the nitrogen piping interfacing with the cold box (upper container) and the four dewars

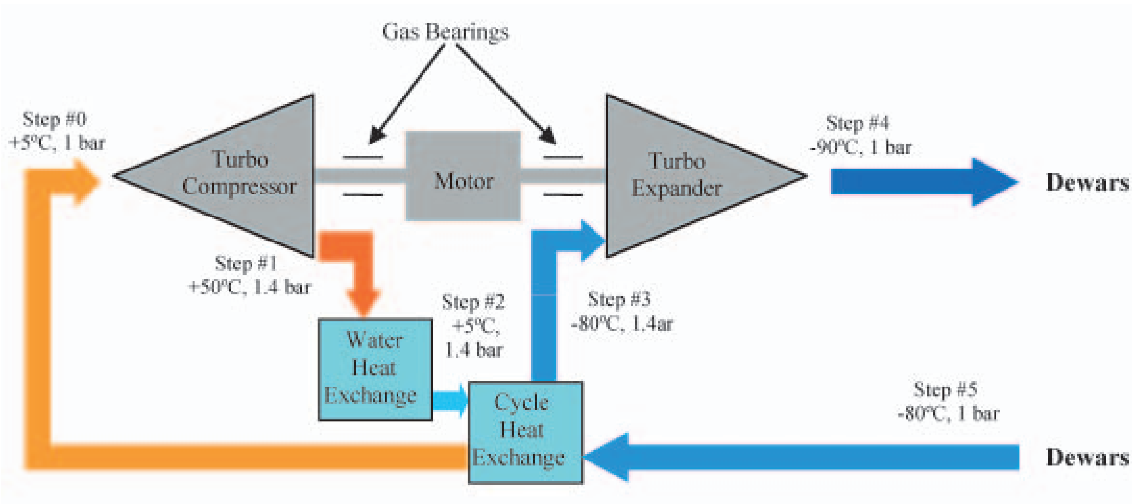


Figure 2. The reverse Brayton thermodynamic cycle

Review in Europe for the first MELFI flight unit will take place in March 2002. The final verification process using the ISS and MPLM simulators located at Kennedy Space Center will start in May 2002. Thereafter, the MELFI first flight unit will be ready for launch in September 2002. It is planned to launch MELFI to the ISS on the ULF-1 flight in January 2003.

The cooling concept

Many trade-off and technology studies were carried out before selecting the cooling concept for MELFI. The key drivers were:

- Low electrical power-budget allocation (900 W) for the size of the cold volume and the low working temperature.
- High reliability (two years of continuous operation) and easy maintenance.
- Very low thermal leaks to cope with a power-off time of 8 hours.
- Very low disturbances to the ISS microgravity environment.
- Very low acoustic-noise requirements.

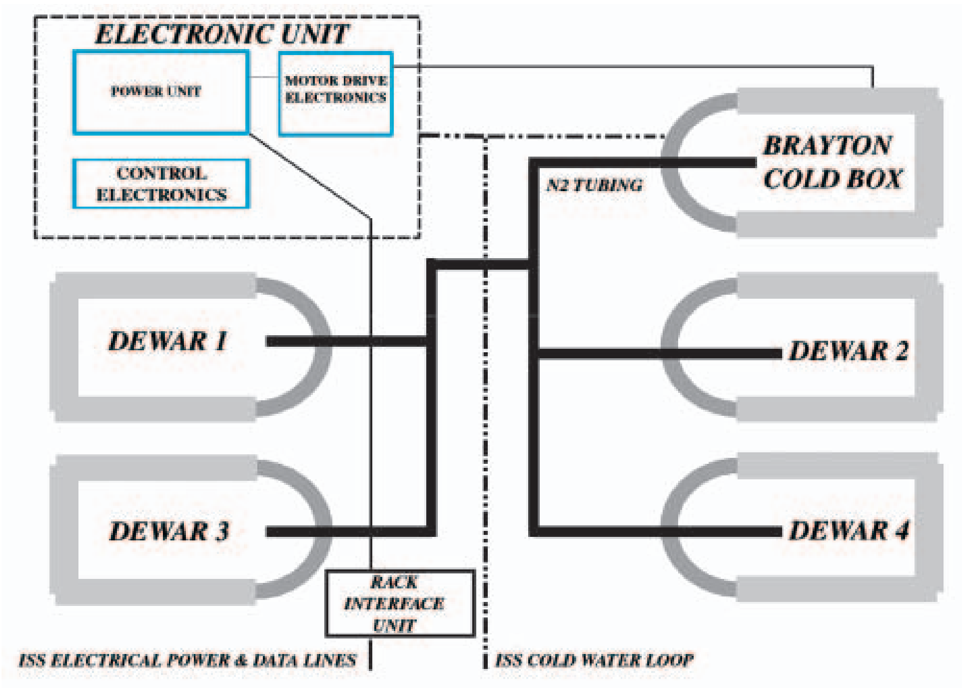


Figure 3. MELFI block diagram

From the outset, the technology for a –80°C freezer was identified as being very difficult to achieve, involving the development of new and very challenging technologies and/or the major adaptation of existing ones.

At the beginning of the 1990's, and after an extensive trade-off with the Stirling cycle, the reverse Brayton cycle was selected for the cooling thermodynamics. It was chosen mainly for its power efficiency in the temperature range of interest and for the reduced microgravity perturbation, thanks to its being a rotating rather than a linear machine. The cold power production relies on a closed thermodynamic loop, in which nitrogen gas is compressed, cooled and expanded to achieve the low temperatures required (Fig. 2). Depending on the electrical power provided to the Brayton machine, the temperature in the expander (step #4) can reach values as low as –95°C.

The heat is removed from the samples by passive means, i.e. conduction and radiation only. Cooling by forced convection was eliminated during the early stages of the project because fans inside the cold cavity are not reliable (easily blocked by ice), increase electrical power consumption, and generate acoustic noise. Also, it is difficult to produce predictable convection flows to the samples, because the flow depends on the filling status. Natural convection due to gravity effects occurs when MELFI is on the ground, but it has been designed to meet the requirements without convection.

The system and its capabilities

Figure 3 shows the main system components. The cooling engine is a Brayton turbo-machine, which provides the flow of cold nitrogen. The rotating components are the turbo-expander, the compressor and the motor magnet, all of which are integrated onto a single shaft supported on gas bearings. This bearing technology was selected because of its long lifetime and the low-perturbation requirements. Two radial bearings support the shaft close to the compressor and turbine wheels, while one axial bearing carries the axial forces introduced in the shaft by the wheels' aerodynamics. The bearings are made of tungsten carbide to withstand the friction that occurs during the starting and stopping of the shaft. The shaft itself can run at speeds in excess of 90 000 rpm, depending on the cooling energy required. The gap between the static and rotating parts of the bearings is only 10 microns. It is therefore very important to balancing the shaft very precisely, and the gas circulating in the cycle must retain very high levels of cleanliness. The machine is cooled by water running through the motor heat exchanger that surrounds the cartridge.

The Brayton motor relies on brushless and sensorless technology. Brushes are not suitable for the high speed and the long-life requirements, and they generate pollution. The sensorless technology was selected for its robustness in the cold environment and because it allows the very high rotor accelerations required to 'lift' the shaft on the gas bearings after just a few turns. Implementation of this technology proved a major challenge, especially in controlling the motor starting phase.

The heat exchangers needed to implement the Brayton thermodynamic cycle are integrated into a closed container called the Cold Box, into which the Brayton machine is inserted to form an integrated assembly called the Brayton Subsystem. A set of tubes (Fig. 1b) distributes the cold nitrogen to four independent cold cavities (the dewars). The supply and return nitrogen flows are in concentric tubes. The nitrogen tubing provides the cooling power to the dewars in a closed loop (i.e. the nitrogen is not in direct contact with the samples in the dewars), at the so-called 'cold fingers' that house the load heat exchangers. A valve at the tip of each cold finger regulates the nitrogen flow. In this way, the temperature in the dewars can be controlled independently in three operating modes (at -80, -26 and +4°C). The dewars are designed to improve the thermal coupling between the samples and the cold fingers. A battery-driven Temperature Data Recorder (TDR) provides the ability to record the temperature in the dewars when MELFI is not powered. All of the areas where the electronics could dissipate significant amounts of heat are instrumented with thermal switches that control potentially hazardous situations within the ISS (fire protection).

The electrical subsystem provides overall control of the MELFI system and powers the Brayton motor and control electronics (Fig. 4). The freezer's continuous availability is crucial to mission success and it is therefore imperative that failure of any sensitive component be recoverable within the maximum time for which MELFI can protect the samples in passive mode, namely 8 hours. Consequently, the Electronics Unit (EU) and the Brayton machine have been designed as Orbital Replaceable Units (ORU), with spares for each available onboard (Fig. 5).

MELFI is integrated into a six-post aluminium rack provided by NASDA, and manufactured by Japan's Ishikawajima-Harina Heavy Industries. The IHI rack was selected because it was already space-qualified, meets the ISPR mechanical interfaces, and is the only existing rack structure able to carry MELFI's maximum mass of about 800 kg.

Designed for an operational lifetime of 10 years, MELFI has been qualified for 15 launches in the MPLM. It has been basically designed for installation in the US Lab module of the ISS, but efforts are underway to interface it with the Japanese Experiment Module (JEM) also.

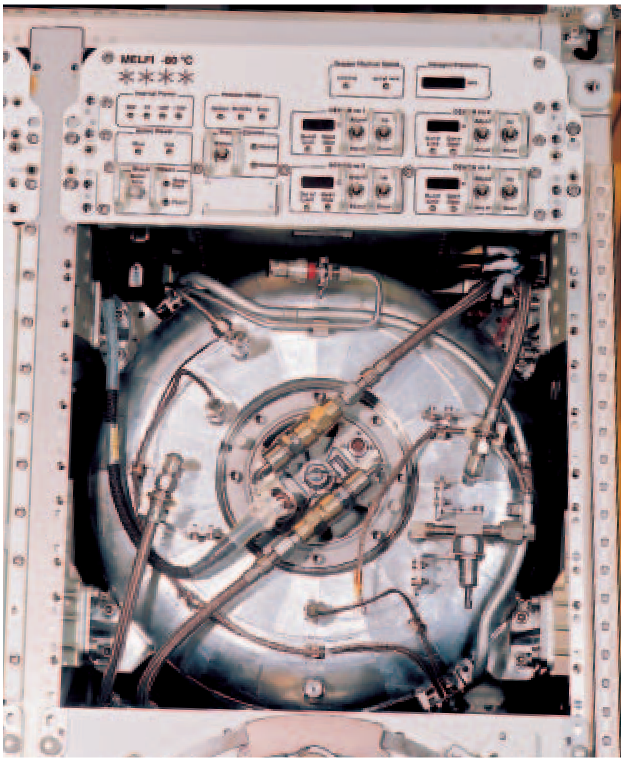
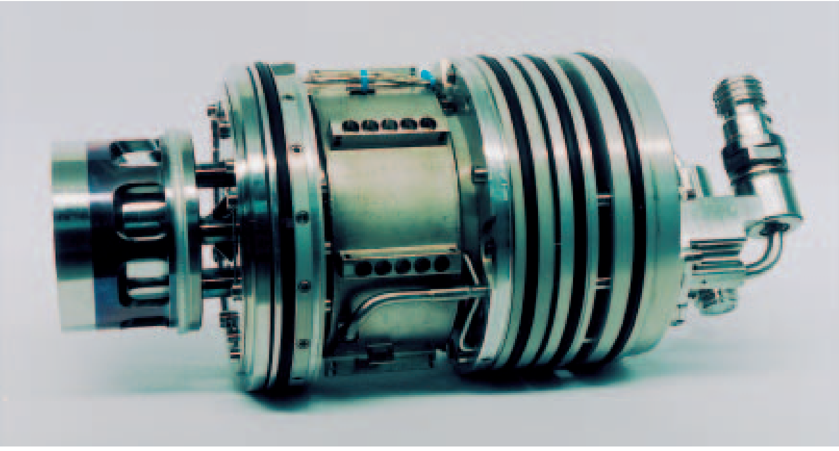


Figure 4. Close-up of the front face of MELFI, showing the active electronic unit control panel (upper right). The spare electronic unit is partially visible to the left of the active one. Below the active electronic unit, the cover plate has been removed to show the Cold Box with the Brayton machine inserted



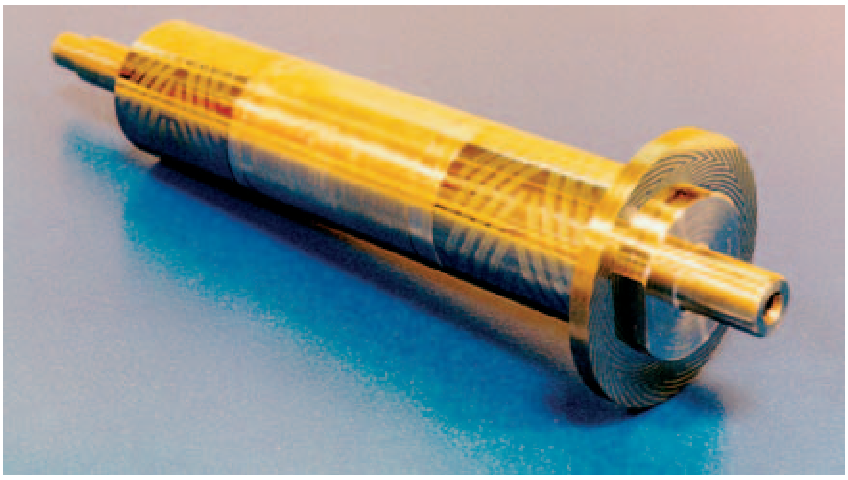
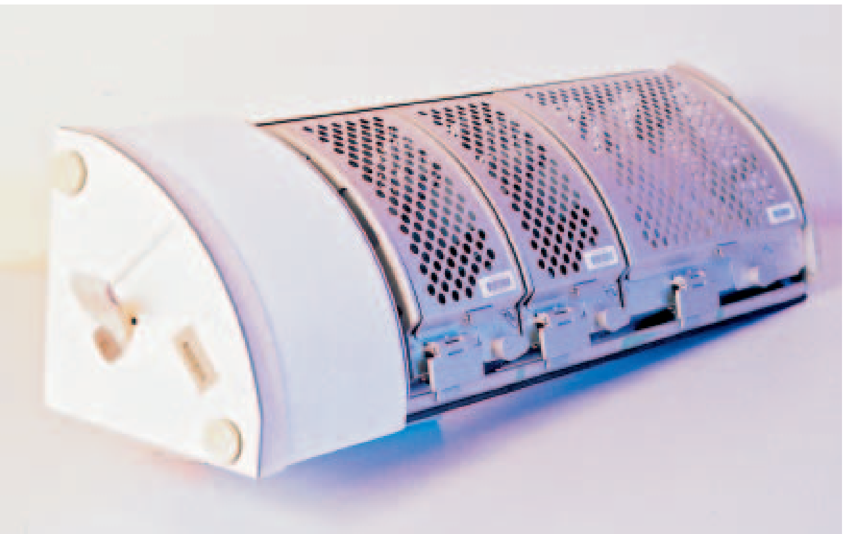


Figure 5. The Brayton machine cartridge (top) and the machine shaft, with compressor and turbine wheels removed to show the radial and axial gas bearings

Figure 6. MELFI tray with the foam insulation block attached to the front of the tray. In this configuration, the tray includes two 1/4-size box modules and one 1/2-size box module

In addition to the four flight units, the project includes the following ground units:
– Laboratory Ground Model (LGM), to be used to support scientific sample accommodation in MELFI and the development of sample integration procedures. This unit is a flight-like stand-alone dewar that includes all the standard sample-accommodation hardware.
– The MELFI Training Unit, which will support active crew training in a flight-like environment.
– The MELFI Engineering Unit, which is a fully integrated rack that will support sustaining-engineering functions.

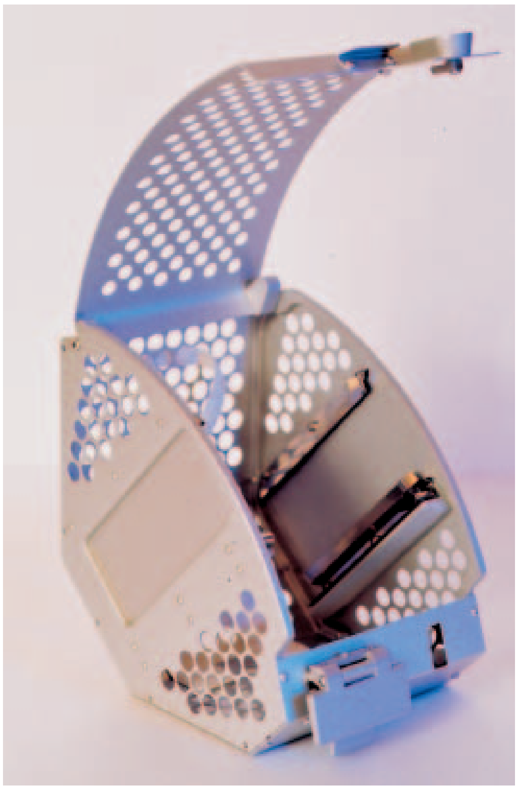


System utilisation

The utilisation of MELFI requires very close co-ordination between the scientists who will conduct the experiments aboard the ISS and the ISS 'cold storage team'. It is important to know well in advance the type of sample, sample container, and cooling and storage requirements, so that the integration of all experiments can be properly planned. The time-lining between the associated experiments and MELFI also has to be correctly co-ordinated.

The utilisation scenario will provide late access to MELFI whilst the Shuttle is on the launch pad. There will also be the possibility to have early access to retrieve the samples once the Shuttle has landed. MELFI provides the necessary ground-support equipment to carry out these operations. In orbit, the samples can be transferred at facility level by exchanging the complete rack, or at tray level by using the MELFI-provided in-orbit transfer bag.

Each dewar includes four trays, each of which can be extracted without disturbing the samples in the other three. In addition, MELFI provides standard accommodation hardware for the insertion of samples of different shapes and sizes (Figs. 6 & 7):
– *Standard vial card:* This card is a flat aluminium plate (10 x 11cm) that can carry vials ranging from 2 to 10 ml in size, and attached by elastic loops. Each card can accommodate up to 20 small vials (10 each side) or 10 large (long) ones (5 each side).



– *Contact cards:* Similar to the standard vial card, but designed to improve the thermal conductivity between the card and the box module, thereby increasing the cooling rate. This card features elastic loops to restrain vials (4 long or 8 small) on one side, and Velcro straps to accommodate irregular shapes (with one flat side) on the other.
– *Standard box modules:* The boxes interface directly to the trays and can store a number of vial cards, vial bags, or any large sample that fits the module. Elastic bands are provided to secure the cards.
– *Receiving box module 1:* This module is identical in size and shape to the standard one, but provides a dedicated interface to hold the Contact Card to improve the thermal conductivity. It also provides a special interface to accommodate 'bottle holders'.
– *Receiving box module 2:* Identical in size and shape to the standard one, it features a solid bottom profile instead of a perforated one for better thermal coupling between the tray, the box module and the inserted samples.

It will be user's responsibility to provide the dedicated accommodation hardware needed for special applications.

In-orbit commissioning
The MELFI system has been fully verified on the ground, with the thermal performances in particular being measured during extensive tests. The cooling performances that will be achieved in orbit have been predicted by analysis, using thermal models correlated during the ground tests. It is necessary to confirm in orbit that those predictions are correct.

In addition to the standard checkout of the general interfacing and system functionality of the MELFI rack, the in-orbit commissioning of the first MELFI flight unit will include verification of the actual cooling performances provided to the samples. For this, ESA has developed the MELFI On-Orbit Commissioning Experiment (MOOCE), which provides additional instrumentation in the dewar cold cavity that holds the scientific samples. MOOCE's 24 thermocouples provide comprehensive temperature mapping of the tray, the box modules and the samples. During the test, the MOOCE's external data-acquisition unit will provide continuous recording and de-multiplexing of the temperature data, which will subsequently be retrieved via the ISS Laptop and the tests results sent to ground using the ISS downlink communication services.

Conclusions
With the MELFI project, ESA and European space industry have jointly developed novel technologies and integrated them into a new space freezer that will provide the scientific community with a large permanent cold-storage facility in space for the first time. The Agency and its MELFI contractors now look forward to contributing their expertise to keeping the MELFI system operational, in order to foster and grow the interest of the scientific community in doing science aboard the ISS in the years to come.

Figure 7. A 1/4-size standard box module full of standard vial cards with frozen samples

Acknowledgement
The success of the MELFI project could not have been achieved without the dedication of the industrial teams. Their flexibility in adapting to the many changes encountered during the early development phases of the ISS infrastructure and in resolving the technical difficulties faced during the development of the challenging technologies involved merits special recognition. The support received from ESA's Technical and Operational Support Directorate at ESTEC, which helped considerably in establishing good technical communications between ESA, NASA, NASDA and the MELFI contractors, is also gratefully acknowledged. Last but not least, thanks also go to those in ESA, NASA and NASDA who have contributed to the complex co-ordination of the many interfaces involved in the implementation of the multilateral Agency agreements.

MSG

M.N. De Parolis
Laboratory Support Equipment Section, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

M. Cole, C. Coker
Microgravity Science and Applications Department, NASA Marshall Space Flight Center, Huntsville, Alabama, USA

M. Zell, A. Schuette
Space Infrastructure, Orbital Systems, Payload & Missions/Operations Centres, Astrium GmbH, Bremen, Germany

Introduction
The Microgravity Science Glovebox (MSG) for the ISS completed its development and verification in Europe in October 2001. After shipment to NASA KSC, it underwent a last series of ISS interface tests before being integrated into the MPLM on 1 March 2002. From May onwards, it will equip the ISS with unique and multidisciplinary laboratory support capabilities.

The MSG has been designed as a modular multi-user facility for performing a wide variety of materials, combustion, fluids and bio-technology investigations in the microgravity environment (Fig. 1). Primarily it provides an enclosed and sealed Work Volume (WV) equipped with lighting, mechanical, electrical, data, gas and vacuum connections, and thermal control. The WV is provided with built-in glove ports for safe handling by the crew and isolates the item under investigation from the operator area and the general ISS environment. An attached Airlock (AL) allows specimens and tools to be inserted or removed during MSG operations with limited environmental exchange between the WV and the ISS cabin. The MSG facility will also accommodate minor repair/servicing of hardware requiring a clean and/or an encapsulated working environment (e.g. the Fluid Science Laboratory's investigation containers).

Figure 1. The Microgravity Science Glovebox (MSG) ready for integration into the MPLM

The design and development of MSG has evolved substantially from the former Spacelab and Mid-deck Gloveboxes that have been flown on numerous Space Shuttle missions and on Mir. Significant enhancements include a substantially larger working volume to house bigger experiments, increased power availability, enhanced diagnostics and data control, and temperature and humidity control.

The facility has been developed by ESA for the NASA/MSFC Microgravity Program Office and includes both flight and ground units. The three ground units – Ground Laboratory Unit, Training Unit and Engineering Unit – have all been delivered to the relevant NASA entres and have already been used extensively by the MSFC Integration Team for experiment development and by the crew for training (Fig. 2).

The development contract was awarded to an industrial team composed of:
– Astrium GmbH (D), Prime Contractor, responsible for System Engineering, Integration and Verification

– Bradford Engineering (NL), responsible for the Core Facility and the Video Drawer
– Verhaert Design and Development (B), responsible for the Airlock and the Outfitting Equipment.

At a later stage, the team was joined by Laben (I), responsible for the Analogue Video Interface Board,0 and Atos-Origin (NL), responsible for the MSG Application Software.

System architecture and characteristics

The MSG has been developed following the science requirements defined by the MSFC Microgravity Science Team, and the functional and interfaces requirements for ISS payloads, defined by NASA Johnson Space Centre (JSC). It is integrated into an ISS Standard Payload Rack (ISPR).

The MSG system architecture (Fig. 3) is built around the Core Facility (CF), hosting the investigations in the WV and providing them with all the resources needed. The other main parts of the facility are:
– the rack infrastructure with ESA's Standard Payload Outfitting Equipment (SPOE), consisting of the Remote Power Distribution Assembly (RPDA), the Standard Payload Computer (SPLC), the Avionics Air Assembly (AAA)
– three ISIS stowage drawers with supporting equipment for payload operations and consumables for facility operations
– the ISIS-based Video Drawer Assembly (VD), supporting optical investigation diagnostics.

Figure 4 shows the Flight Unit (FU) rack during Electro-Magnetic Compatibility (EMC) testing at Astrium.

The MSG facility has been built for a projected ten years of operational use in orbit. It will be initially accommodated in the United States Laboratory (USLab), but could be moved at a later stage to the European Columbus Laboratory.

Core-Facility capabilities

The Core Facility includes the large Working Volume (WV), the Airlock and electronics for control, housekeeping and investigation resources and it occupies the upper half of the overall rack (Fig. 4). The Command and Monitoring Panel (CMP), located on top of the WV for ease of crew operation, monitors the facility's status and performance and provides all means for the manual operation of MSG by the crew.

The WV is a large confined volume of 255 litres offering two levels of containment for investigations. The first level is achieved by the physical barrier of the wall and the second through an under-pressure in the WV compared with the surrounding environment, i.e. in the event of a leak, any airflow will always go into and be confined within the WV. The continuous air circulation inside the WV and Airlock that maintains the under-pressure is filtered and cooled, providing both a clean-room environment and the possibility to remove up to 200 W of thermal energy from the item under investigation.

Figure 2. The MSG Training Unit

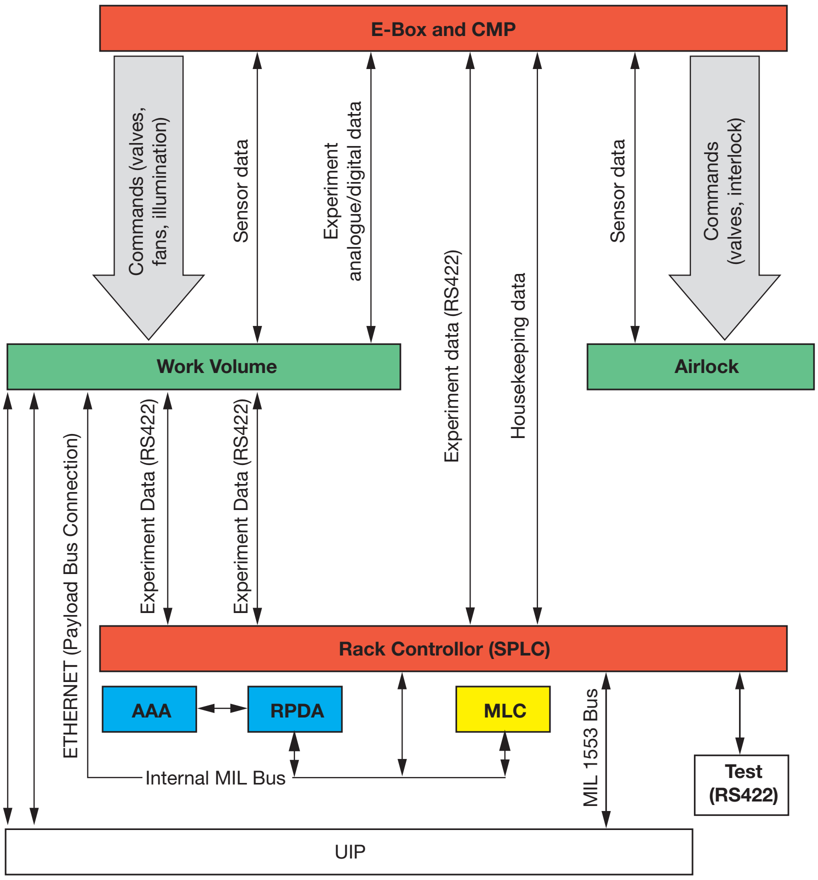


Figure 3. The MSG system architecture

Figure 4. The MSG flight-unit rack during EMC testing at Astrium

Figure 5. The MSG Work Volume (WV)

Figure 6. The MSG Airlock

The WV is provided with front and side ports for access/loading, all of which can be equipped with gloves. The WV can be slid in and out of the rack assembly to afford access to the side ports for the initial introduction and manipulation of investigations, and to fix accessories such as the cameras to selected mounting points. The entire front surface of the WV is a Lexan window, which provides the operator with a wide viewing angle. For investigations needing a darkened environment, the window and the lateral panels of the WV can be covered with special stray-light covers.

The large Work Volume and the large access ports make it possible to perform large and complex investigations, and two investigations can be accommodated simultaneously. Other experiments can be bolted to the bottom of the WV and to the left part of the back wall (Fig. 5). The WV's internal lighting can be dimmed, and there is also a spotlight to provide illumination in restricted areas. An Investigation Cold Plate embedded in the floor of the WV allows removal of up to 800 W of heat from the baseplate of the investigations.

The Airlock (Fig. 6) provides access through a sealed and tiltable top lid and has its own WV-independent internal lighting.

Video Assembly characteristics

The Video Assembly (VA) has been contributed to the MSG project by the Dutch Agency for Space (NIVR). It is integrated into a dedicated active International Subrack Interface Standard (ISIS) drawer, provided with a sliding top lid for easy access (Fig. 7). It is a self-standing subsystem including 4 colour cameras, 2 monitors, 2 analogue and 2 digital recorders, a touch pad, power distribution, a power and data line and a controller board. Thermal control for the powered components inside the Video Drawer is provided by a rear suction fan for air circulation to transfer a maximum of 125 W to the MSG internal air-cooling loop.

The VA has a dedicated controller that allows the user to command the video system via an input device connected to the RS-422 serial interface (normally connected to the MSG SPLC) or via the touch pad. The functionality provided through these digital interfaces is in addition to the fully hardwired command possibility via the drawer front-panel switches and the individual local command functions on the recorder, monitor and camera units themselves.

Three dedicated, sealed feed-through ports in the front corners of the Work Volume allow the use of all external MSG video components (video cameras, monitors, touch pad, etc.) within the WV.

Command and control capability

The MSG facility will allow both unattended and crew-attended investigations, and therefore many different command and control capabilities are offered. In the local mode, the crew can introduce commands via the Control and Monitoring Panel (CMP) and, in some

cases and for a limited set of commands, also through the Internal Control Panel (ICP) inside the Working Volume. In the remote mode, commanding is possible via:
- the MLC, which can be hooked up to the MSG internal MIL 1553 Bus at the MSG front panel. A subset of non-safety related commands is available.
- the MLC connected to the ISS MIL 1553 Bus, from the MSG
- the US Lab System via the payload MDM
- by ground commands, which are accepted in parallel with CMP controls; this mode would also allow unattended operations for non-hazardous investigations or unattended standby control.

Figure 7. The MSG Video Assembly, contributed by NIVR (NL)

Facility operations

The MSG rack will be launched in passive mode in the MPLM on ISS Utilisation Flight No.2 (UF-2), foreseen for May 2002. It will then be moved to its location in US Lab, for in-orbit commissioning. After the successful completion of this phase, it will be ready to start its operational life.

The experiments will be launched/retrieved within stowage drawers (Express Racks or Resupply/Stowage Racks) or Shuttle Mid-deck Lockers. During certain MSG operations (such as cleaning of the WV, filter change outs) they can be stored temporarily within other MSG racks and stowage drawers.

The MSG can operate in an open mode, with air circulating from the WV to the MSG rack interior, and in a closed mode with air circulating only within the Work Volume. There is also the possibility to maintain in an inert dry-nitrogen atmosphere such that the oxygen volume is kept to 10% or less.

The MSG will also accommodate ISS Laboratory Support Equipment (LSE), such as general-purpose tools, fluid-handling tools, cleaning equipment, mass-measurement devices, a pH meter, a dissecting microscope and supplies, digital multi-meters and a compound microscope. Apart from the equipment required for the general upkeep of the WV, a significant amount of resources and outfitting equipment is available for MSG science investigations.

Science and information interface

Glovebox investigations cover four major disciplines: material science, biotechnology, fluid science and combustion science. A similar peer-review process to that used for earlier Space Shuttle missions is being applied to select the investigations to be flown in the MSG by NASA's Microgravity Research Program Office (MRPO). ESA has utilisation rights for this facility and will therefore pre-screen the European-proposed investigations and then present them to NASA for final approval.

Both NASA and ESA periodically announce microgravity research opportunities via NASA Research Announcements (NRAs) and ESA Announcements of Opportunity (AOs), respectively. More details can be found at: http://floyd.msfc.nasa.gov/msg, and http://www.esa.int/export/esaHS/research.html.

To assist potential Principal Investigators (PIs), there is a MSG Investigation Integration Team located at NASA's Marshall Space Flight Center (MSFC), composed of a core group of managers, engineers, and support personnel. This Team oversees the interface and safety requirements, the schedule for meeting ISS template milestones, the administrative support for documenting interfaces to the MSG facility, and the investigation manifesting, analytical integration, and flight operations. It also supports the investigation development teams in ensuring that the engineering interfaces to the MSG and the ISS are met. The investigation integration process and schedule are defined in the Microgravity Science Glovebox Investigation Integration Plan (MSFC-PLAN-3052), which also addresses the implementation activities and the development of data products.

Acknowledgements

The Microgravity Science Glovebox's development, integration and testing have involved many different individuals and organizations, who have contributed greatly to the success of this facility. Due acknowledgements are made to the MSG Industrial Team, the ESTEC Technical and Operational Support Directorate team, as well as the MSG Teams at NASA/MSFC. We all look forward to many years of successful MSG scientific utilization!

Cryosystem

M.N. De Parolis
Laboratory Support Equipment Section, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

W. Ruemmele
Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, USA

Introduction
The Cryosystem is an ultra-low-temperature facility for supporting life-sciences payloads in space. It brings together a unique set of facilities for the optimal preparation, preservation and storage of biological samples and protein crystals at cryogenic temperatures. Thanks to its ultra-rapid cooling capability and its relatively large cold volume, it will provide a great improvement in the quality and quantity of science investigations in the fields of life sciences, physiology and biotechnology.

The Cryosystem will complete in the ultra-low temperature field (–180°C) the range of freezers provided by ESA to NASA for use on board the International Space Station (ISS), the other two systems being MELFI working in the temperature range from +4 to –80°C, and the Crew Refrigerator Freezer covering the range from +4 to –26°C.

During the Cryosystem's preliminary design phase (Phase-B), which has started in February 2002, prototypes of the complete freezers as well as some in-orbit support equipment will be developed to prove the feasibility of the proposed concepts. The design phase is therefore foreseen to last about 18 months, concluding with a Preliminary Design Review (PDR). The subsequent main development phase (Phase-C/D) will be concluded with the delivery of the last freezer unit, in 2008.

Since the ISS assembly sequence is currently under review, the first launch of a Cryosystem element is not yet fixed, but the On-Orbit Preservation Rack (OPAR) could be launched in the Centrifuge Accom-modation Module (CAM) not earlier than January 2008.

The Cryosystem industrial development team selected consists of:
– Astrium (Germany), Prime Contractor, responsible for systems engineering, integration and verification, as well as for development of the rack infrastructure
– L'Air Liquide (France), responsible for the cryogenic cubsystem, including the freezer drawers and the associated orbital and ground-support equipment
– Thales Cryogenics (The Netherlands), which will be responsible for the cryocooler's development
– Damec (Denmark), responsible for the science interfaces and utilisation hardware.

System architecture and operational scenario
The Cryosystem is being developed to meet the science requirements defined by the NASA Science Working Group, and the functional and interface requirements for ISS payloads defined by NASA Johnson Space Center (JSC).

The heart of the system is the Cryogenic Storage and Quick/Snap Combo Freezer. Contained within one drawer, it will support the following functions:
– storage and preservation of already frozen biological samples and supplies contained in vials
– ultra-rapid cooling and 'snap freezing' of various specimens, such as tissues, eggs and cells
– transportation to and from orbit of specimens and supplies
– transportation of specimens to/from other ISS racks, such as the Life Science Glovebox (LSG) and X-Ray Diffraction Facility (XCF).

The Orbital Support Equipment (OSE), consisting of tools and ancillaries needed for the freezer operations (including maintenance) in orbit, will be stowed in a dedicated drawer.

The Cryorack is an ISS Standard Payload Rack (ISPR) outfitted with a liner (mechanical infrastructure) and subsystems to support operation and transportation of the freezers, and the transportation of passive payloads in the Mini Pressurised Logistic Module (MPLM).

NASA and ESA are also considering developing a second type of combo freezer to allow the ultra-rapid freezing and storage of specimens contained in bags, such as those used for tissue cultures.

The system will have a flexible and variable architecture, depending on the utilization needs of the various freezers. The first Cryorack will be transported to orbit within the Centrifuge Accommodation Module (CAM), and will remain there for its projected design lifetime of ten years. The other two Cryoracks will ensure the cyclical up- and down-loading of the freezers and the specimens therein. Both will support multiple missions, including installation in the MPLM, installation of freezers, transportation to and from orbit, removal from the MPLM, and refurbishment before the next mission (Fig. 1).

The Cryorack may accommodate up to three freezer drawers (for vials or for bags) and a number of International Subrack Interface Standard (ISIS) drawers, containing either the freezer orbital support equipment or additional passive payloads (Fig. 2). The ISS Cold Stowage Working Group will be responsible for defining the configuration needed for each increment, depending on the experiments planned and on the availability of resources on the MPLM and ISS.

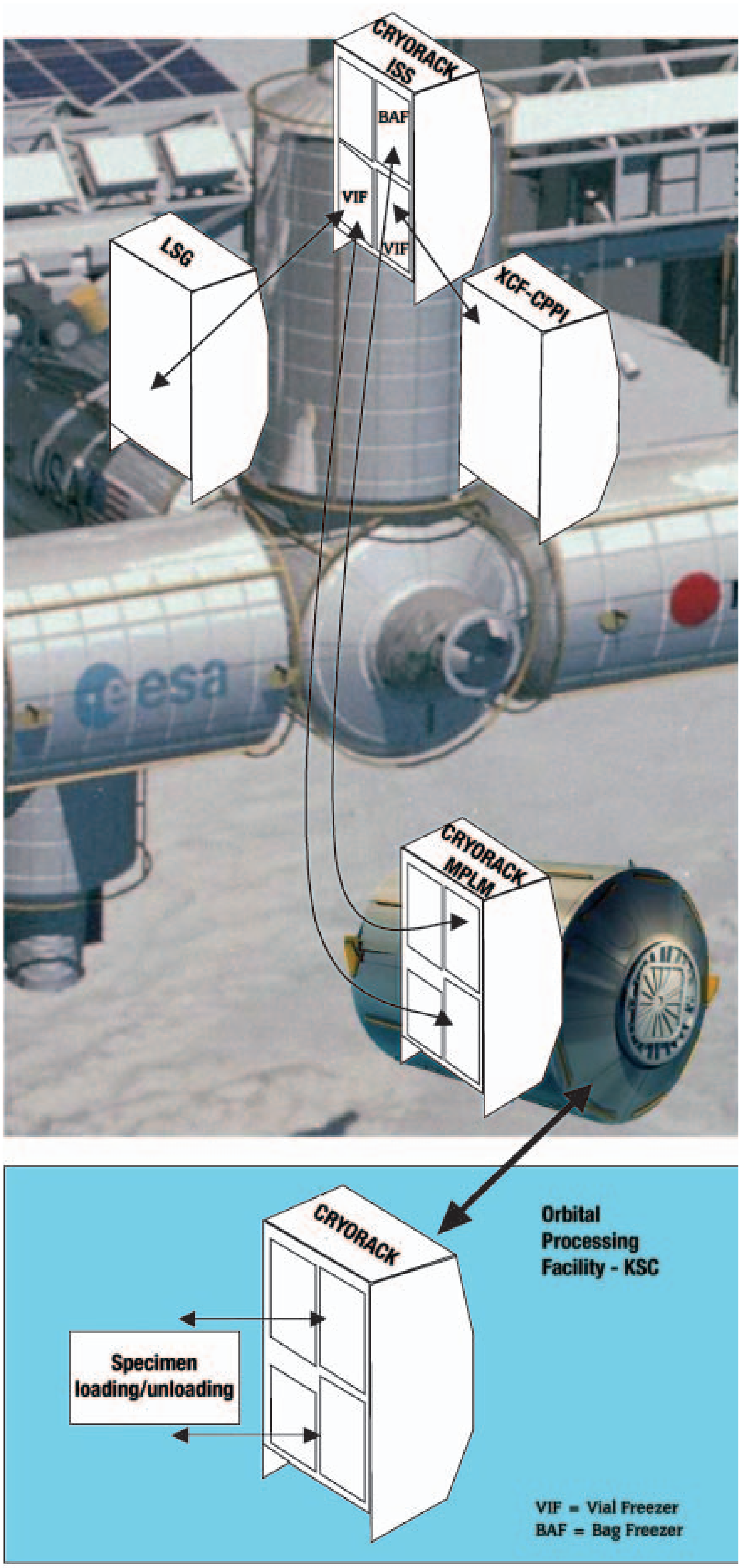


Figure 1. The Cryosystem operating scenario (courtesy of Astrium)

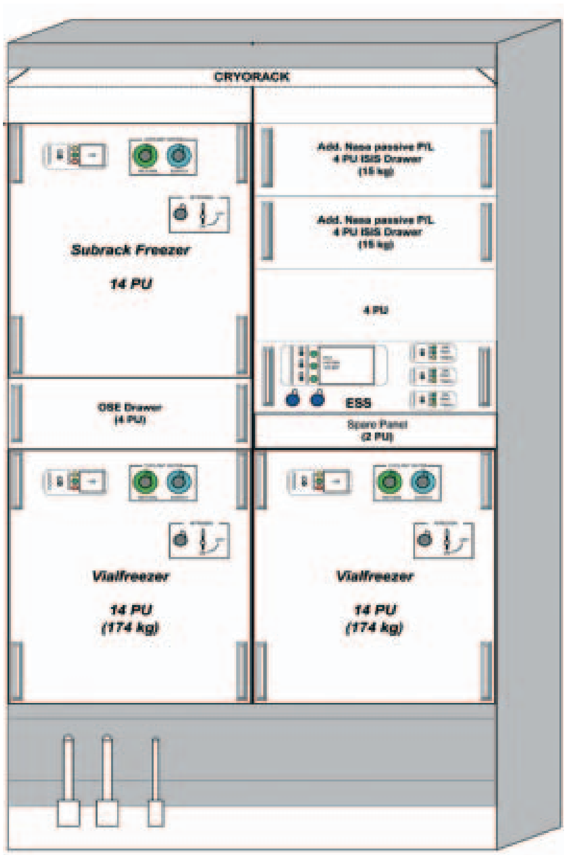


Figure 2. Cryorack basic outfitting accommodation (courtesy of Astrium)

The Cryorack basic structure will be an ISS Standard Payload Rack (ISPR), provided by NASA but suitably modified to allow an optimal design for the freezers and their infrastructure. The rack will be outfitted to accommodate the freezer drawers, the electrical subsystem (ESS) drawer, and the additional ISIS drawers for the passive payloads and the Orbital Support Equipment. A water loop will ensure optimal cooling of the freezers and the subsystems needed for their correct operation. Cryorack will provide the necessary power, thermal control, and command and data handling. In addition, OPAR may include a system for supplying gaseous nitrogen for humidity control within the freezers' cold volumes.

Cryogenic storage and quick/snap combo freezer

The freezer will be integrated into a drawer 14 panel units high (about 650 mm) and half a rack in width (about 450 mm). The freezer itself will be a cylindrical vessel (dewar), vacuum-insulated, and provided with a complex system of small ports to avoid heat leakage, whilst still allowing for the loading/unloading of the specimen containers (Fig. 3).

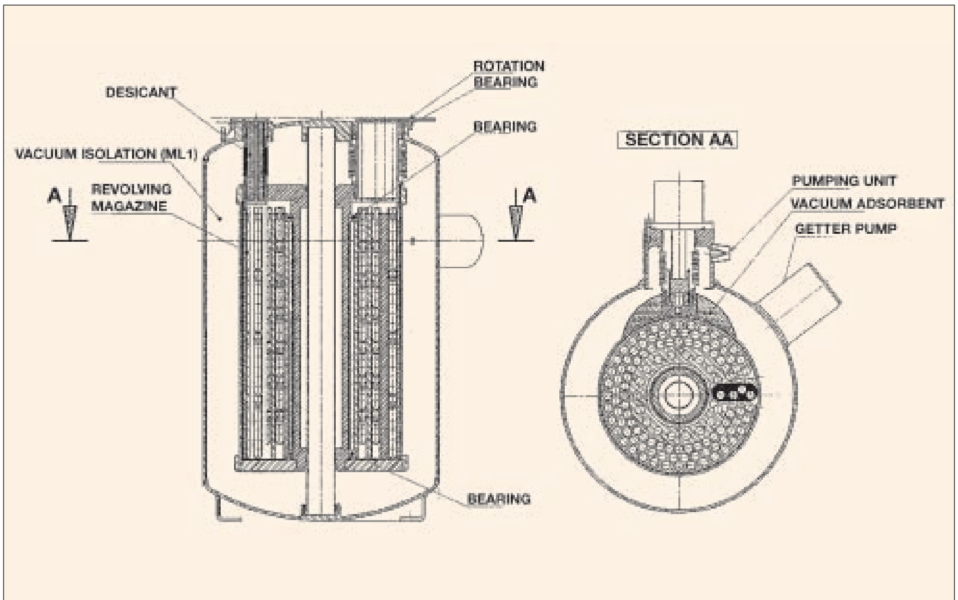


Figure 3. Schematic of vial freezer dewar

Cooling will be provided by a Stirling cooler, connected via a cold finger to the dewar's internal structure. Given the severity of the cooling requirements and the ten-year lifetime requirement, adaptation of an existing cooler – used for military applications – has already been initiated by the companies involved (Thales and L'Air Liquide). Figure 4 shows the development-model cooler displacer provided with a flexure bearing.

Figure 4. The Cryocooler's displacer and flexure bearing (courtesy of Thales/L'Air Liquide)

The dewar will hold about 800 2-ml or 400 5-ml vials, or a combination of the two. The containers will be arranged as a concentric array of tubes providing: maintenance of the required temperature, support and restraint during critical orbital phases, and the possibility of indexing every container. In particular, a carrousel mechanism integrated inside the dewar allows three-axis identification (angular, radial and in-depth) of each container. Both the dewar structure and each container will therefore be suitably labelled and coded according to the ISS Inventory Management System.

The freezer will have four basic modes of operation: storage and transportation, quick freezing, snap freezing, and collection of already processed and frozen protein crystals. To accomplish this, it will be able to interface with and to operate in different racks: the Cryorack, which is its 'home rack', the Life Science Glovebox (LSG), and the X-Ray Crystallography Facility (XCF)/Crystal Preparation Prime Item (CPPI).

Transportation of specimens and supplies to/from orbit

The Investigators' specimens and supplies will be transported from their laboratories to the Kennedy Space Center (KSC) processing facilities using dedicated ground dewars provided by the Cryosystem developer. The specimens can be stored in the freezer either before its installation in the MPLM, after its installation in the MPLM whilst still at the processing facility, or during the late-access operations with the MPLM/STS already on the launch pad.

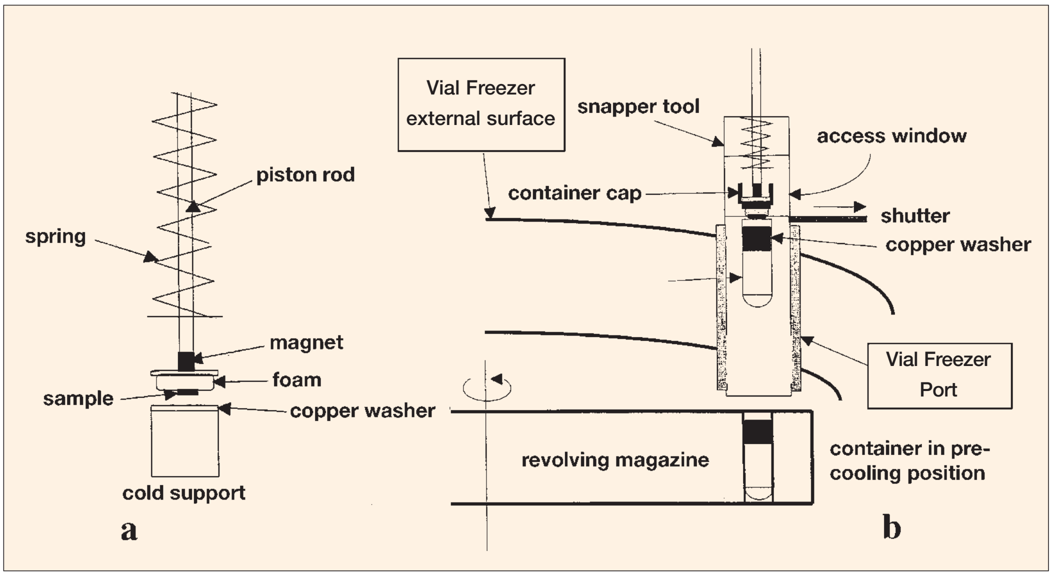


Figure 5. (a) The snap-freezing tool. (b) Operating configuration at the vial freezer port (courtesy of L'Air Liquide)

The freezer will receive all necessary power, cooling and data-handling resources from the MPLM, except for certain periods during the launch and landing phases. It is therefore designed to have sufficient thermal inertia to maintain the required temperature inside the cold volume (i.e. -180 ± 5°C) during those periods. The cold-volume temperature will be monitored throughout the specimens' lifetime in order to provide the Investigators with data to confirm the 'suitability' of their specimens for their investigations.

After the docking of the MPLM to the ISS, the freezer will be removed from Cryorack/MPLM and transported and installed by the crew into the Cryorack location in CAM. The reverse operation will be performed after the freezer has completed its mission.

Transportation of specimens to other ISS racks
A challenging requirement for the vial freezer is the ability to withstand multiple cycles of installation/de-installation in various ISS racks, as it continuously 'travels' from its home rack (Cryorack) to either the LSG or the XCF-CPPI racks and back. Wear problems are to be expected for all mechanically interfaced parts such as connectors and drawer slides.

Quick-freezing function
Quick freezing occurs when a biological specimen (plant tissue, animal tissue, animal body fluid, etc.) is removed surgically (or equivalent) from the host, inserted into a specimen container and subsequently cooled-down to below prescribed temperature limits over a period of several seconds to minutes.

These quick-freezing operations will occur with the freezer installed at the LSG. The surgical operations will be performed on the table inside the LSG working volume, while the quick-freezing tools will be contained inside the freezer. The crew will remove the tools from the freezer, transfer the sample from the surgical table to the dedicated tool and then re-insert the specimen container into the freezer's quick-freeze zone. The vial freezer will be able to cool-down a 5-ml vial filled with standard saline solution from ambient temperature to –160°C in less than 10 minutes. The freezer will be able to support multiple quick-freezing operations, according to defined scenarios, before it needs to be transferred back to OPAR for recovery and storage.

Snap freezing
Snap freezing is a process whereby exposed plant or animal tissue is rapidly frozen so that sub-cellular structure is preserved during the freezing process. During ordinary specimen freezing, the water contained within the cell forms large ice crystals that destroy sub-cellular structures. With snap-freezing, the surface of the material is frozen almost instantaneously, so that amorphous ice or very small ice crystals, which do not destroy sub-cellular structure, are formed.

Since the cooling is delivered to the specimen surface and then propagates through the material, the practical limitations of this process limit 'good freezing' to a thin region (about 15 microns thick) near the specimen's surface. The vial freezer will be able to snap-freeze samples with an area of about 36 mm^2 while having at the least 10% of this area free from cellular damage. These snap-freezing operations will take place with the freezer installed at the LSG.

A prototype snap-freezing device (Fig. 5) has demonstrated a success rate of about 80%, which is comparable with the performance of similar equipment used in ground laboratories.

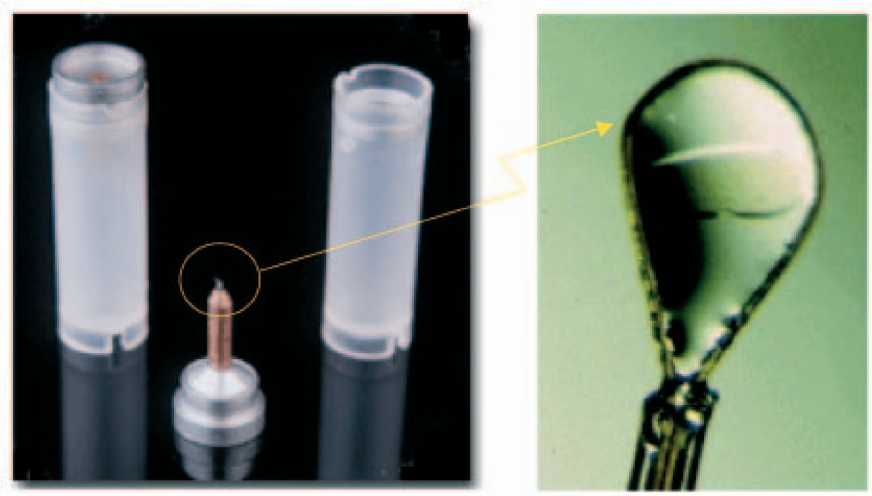


Figure 6. Cryovial, and a Cryoloop with a 'hanging' drop of protein crystal solution (photos courtesy of Hampton Research and Lawrence Livermore National Laboratory, respectively)

Protein crystal storage

The XCF is a NASA-integrated rack hosting various sub-facilities for the growth, preparation, mounting and freezing of protein crystals. In particular, the CPPI (Crystal Preparation Prime Item) will take care of the last two operations and will move the frozen containers robotically to a location where the freezer transfer port can be installed. The CPPI equipment will 'fish' the crystal from the growth solution, mount it on a 'cryoloop' and insert the latter into a suitable vial (Fig. 6).

If the vial freezer collects a specimen in unpowered status, the collection time will be limited to one hour to maintain the very strict temperature requirement for the protein crystals (-180 ± 5°C). The interfaces between the freezer and the CPPI, as well as the number of containers that can be transferred in one hour, have to be defined during the detailed design phases for both the freezer and the CPPI.

Combo Storage Freezer for bags

At the end of the Cryosystem design phase (Phase-A), it became evident that 2 and 5-ml vials would not be the only containers needed for life-science experiments. In particular, tissue cultures would require use of bigger and more complex 'bags' (Fig. 7), where the tissue can grow without any intervention from the crew other than the injection of the growth solution. These samples also need to be stored at cryogenic temperatures after growth. However, the vial freezer defined above cannot be used for this because mixing of the two container types and the various sizes would greatly reduce either the available capacity or the quick/snap-freezing performance of the freezer, or both. For this reason, NASA required ESA to propose an additional combo freezer to host those particular containers. NASA will take a decision regarding the implementation of the bag freezer in the second quarter of 2002.

If NASA decides to fund this option, the bag freezer will be very similar to the previous one. The only differences will be in the internal outfitting of the dewar, since the bags are bigger and have a more complex configuration than the vials. The foreseen dewar capacity could be around 150 10-ml or 80 30-ml bags, or a combination of the two sizes. In addition, it will be possible to store about 40 sealed syringes (or other cylindrically shaped containers) of 10-ml capacity. This will allow the uploading of growth solutions at very low temperatures, to be injected into bags or vials for life-science experiments.

The quick-freezing capability will be implemented using dedicated outfitting. Snap-freezing is not possible because the specimen is not directly accessible, being confined within the bag. The bag freezer will be used only at the Cryorack, because the specimen will be contained within the bags and will not require a closed and sealed environment for its development.

The supplies and specimens will be transported to/from orbit using the same scenario as for the vial freezer.

Acknowledgements

The authors wish to thank the industrial contractors for providing preliminary drawings and descriptions of the hardware, and the ESA and NASA Cryosystem teams for their hard work during the requirement consolidation phase.

Figure 7. Biotechnology bags inserted into a metal frame (courtesy of NASA)

Hexapod

P.C. Galeone
Space Station Utilisation Division, ESA Directorate of Manned Spaceflight and Microgravity, ESTEC, Noordwijk, The Netherlands

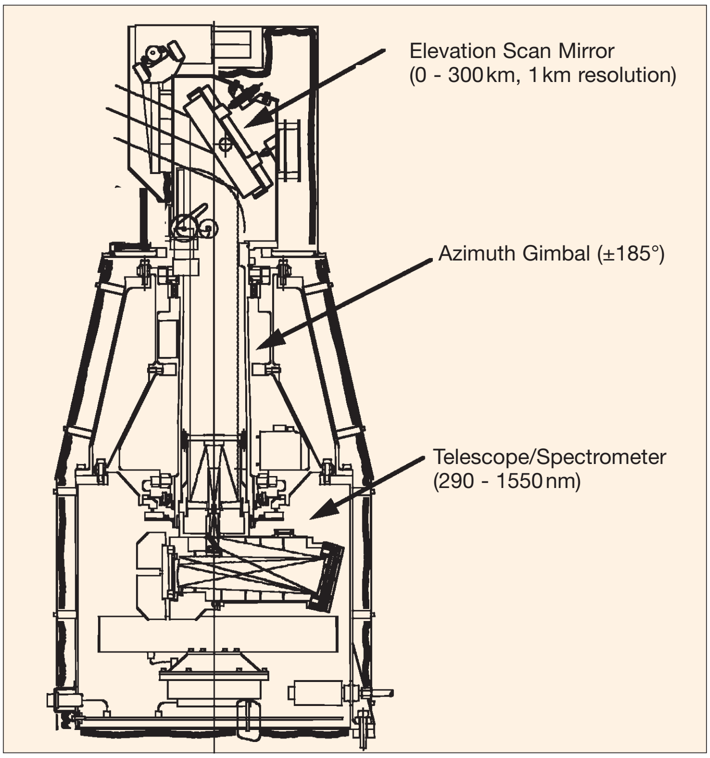
L. Szatkowski, O.H. Bradley
NASA Langley Research Centre, Hampton, Virginia, USA

R. Trucco, B. Musetti
Alenia Spazio, Turin, Italy

Introduction

SAGE III (Stratospheric Aerosol and Gas Experiment), an Earth-observation instrument developed by NASA's Langley Research Center (LaRC), was one of the first scientific external payloads selected for the International Space Station (Fig. 1). It was conceived to fly on a spacecraft able to provide ± 1 degree pointing accuracy. Since the ISS's attitude can vary by several degrees over a long period, it was therefore necessary to provide a dedicated nadir-pointing system. For this task, NASA selected the hexapod-based pointing system ('Hexapod' for short) included by ESA in the list of proposed European contributions to the ISS early utilisation phase. Launch is currently scheduled with assembly flight UF-3, although this could be modified by revisions in the ISS assembly sequence.

The development of SAGE III and the Hexapod were both approved and funded in 1994. The contract for the Hexapod design phase (Phase-B) was awarded by ESA to Alenia Spazio (I) in 1995, with Carlo Gavazzi Space (I) and ADS Italia as subcontractors. The main development phase (Phase-C/D) was initiated at the beginning of 1998, with Alenia Spazio (Prime Contractor) and Carlo Gavazzi Space. The Critical Design Review (CDR) was completed in November 2000, and flight-unit completion is scheduled by mid-2002. LaRC will then be responsible for the overall Hexapod and SAGE III payload integration.



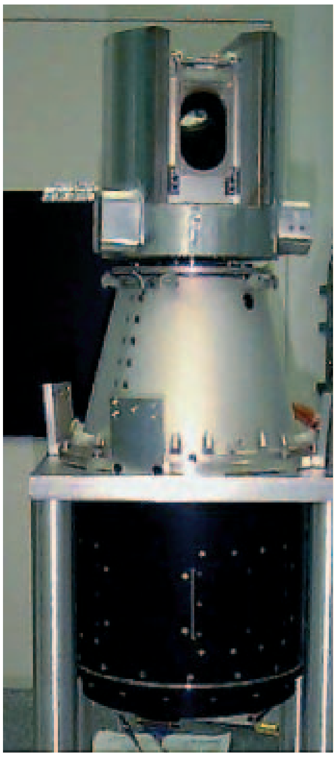


Figure 1. The SAGE III instrument's key elements

The SAGE III Scientific Instrument

SAGE III is designed for the global monitoring of the vertical distributions of stratospheric aerosols, ozone, water vapour, nitrogen dioxide and trioxide, chlorine dioxide, and temperature from Earth orbit. It uses spectrographic techniques based on light-source occultation, which typically offer the capability for self-calibration, high vertical resolution, high signal-to-noise ratio, and excellent inversion accuracy.

The core sensor is a spectrometer able to measure the extinction of both solar and lunar radiation through the Earth's atmosphere during occultation events, between 290 and 1550 nm with 1 nm spectral resolution and 1 km vertical altitude resolution. The instrument incorporates a unique charge-coupled detector (CCD) array and a single photodiode detector in the focal plane to perform the science measurements. The sensor assembly provides spatial resolution over an altitude range from cloud-top (or the Earth's surface on cloud-free days) to 300 km. Science data are taken up to an altitude of 150 km. Data sequences are also taken between 150 and 300 km altitude on some orbits to radiometrically and spectrally calibrate the instrument.

Mission overview

The Express Pallet System (ExPS) is both a Shuttle carrier and an in-orbit payload accommodation facility, which can be robotically installed on the truss of the ISS. It accommodates payloads mounted on Express Pallet Adapters (ExPA). The ExPA hosting Hexapod and SAGE III is integrated onto the ExPS on the ground, and is used as the payload carrier at launch. Hexapod will be launched unpowered, with the Orbiter providing power for its 'stay-alive' heaters after the payload-bay doors are opened in orbit.

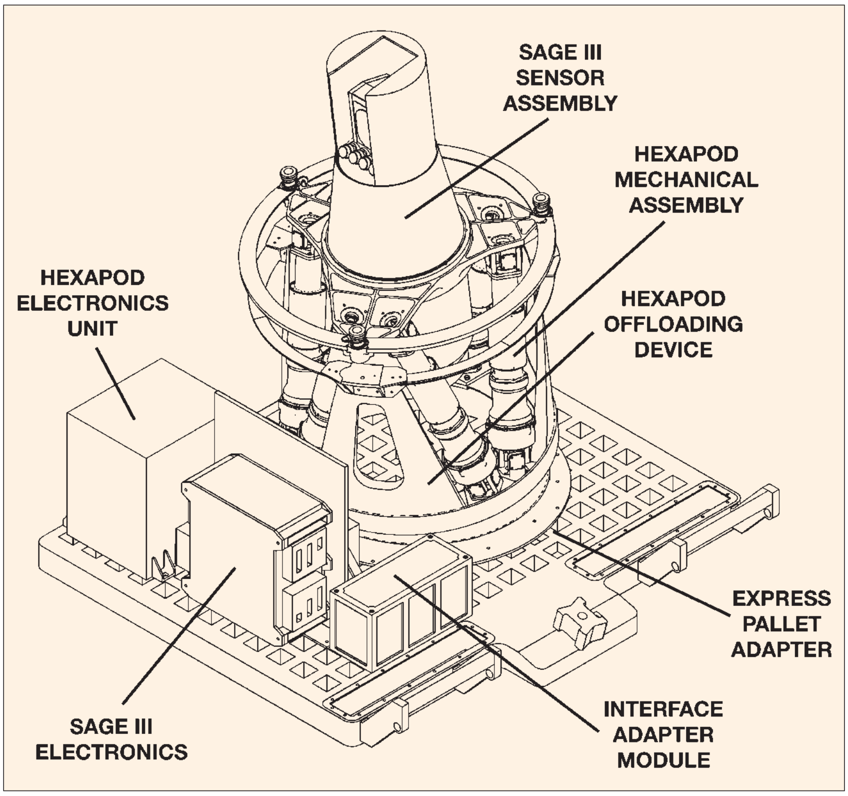


Figure 2. The Hexapod system integrated with SAGE III (together with the electronics boxes for both) on the Express Pallet Adapter

The complete ExPS will be moved robotically from the Shuttle and transported by using the ISS Mobile Base System (MBS) to its nominal in-orbit accommodation site. The location assigned is the nadir-starboard outer payload attachment site of ISS truss segment S3 (close to the thermal radiator), with Hexapod and SAGE III accommodated on the ExPA installed at the ExPS corner location in the ram-outboard direction.

Hexapod and SAGE III will be activated and start their science mission only after the ExPS is connected at its attachment site. Both are designed for five years of in-orbit operation without maintenance. Users will, however, be able to up-link Hexapod flight-software updates.

At the end of their mission, Hexapod and SAGE III will be removed from the ExPS along with their ExPA. They will remain unpowered during the transfer to the Shuttle Orbiter and during Earth re-entry. Fail-safe brakes in the Hexapod linear actuators ensure that accelerations during reentry do not cause payload displacement in the cargo bay.

Hexapod design characteristics

The key performance requirements for Hexapod consist of achieving a pointing accuracy of ±90 arcsec in the nadir direction – with a pointing stability of 0.0025 deg/sec, a pointing range equivalent to an 8 deg cone, and with an angular pointing rate of at least 1.2 deg/sec – and accommodating a 35 kg SAGE III sensor assembly.

Hexapod determines attitude based on the ISS-provided attitude state vector (attitude quaternions and GPS data), and applies an attitude correction matrix to take into account the local attitude deviations actually experienced at the mounting location. The matrix is defined on the ground, based on the actual SAGE III measurements and uplinked to Hexapod (via SAGE III) along with the telecommand data for the pointing manoeuvre.

The Hexapod flight unit, including the electronics, weighs 116 kg. The overall payload, including the SAGE III electronics boxes, harness and other system-level outfitting, will be close to the 225 kg allowance for the ExPA. The accommodation of the SAGE III sensor assembly in the volume between the Hexapod's legs takes best advantage of the specific geometry of this type of mechanism (Fig. 2).

Hexapod's power consumption in orbit varies according to the operating mode. It ranges between the power needed to survive ExPA cold phases (the in-orbit stay-alive heaters require around 100 W, with thermostatic control), and a maximum operating power of 435 W during the execution of pointing manoeuvres when all legs are moving simultaneously (not required in all cases). The estimated average power consumption is about 120 W, given that the execution of a complete pointing manoeuvre takes just a few seconds.

Hexapod consists of two main parts: the Electronic Unit (HEU), and the Mechanical Assembly (HMA). The HEU is the integrated power and control unit that handles power distribution, telemetry and telecommand management, data processing, and command and control. It provides the computer control for the co-ordinated movement of the six linear actuators. Hexapod flight software resides on the Standard Payload Computer (SPLC).

The HMA includes six electromechanical linear actuators, arranged as three trapezoids and connected by means of 12 universal joints to a bottom flange and to an upper platform. The latter's attitude and position are determined in six degrees of freedom (translation along and rotation about all orthogonal axes in 3D space) by the combination of the lengths of the six linear actuators. The resulting configuration is a statically determined structure that enables the stroke of each individual linear actuator to be changed without causing internal stresses in the mechanism. The bottom flange is fixed to the ExPA and the upper platform accommodates the SAGE III sensor assembly. The Hexapod's bottom flange includes an offset-wedge function, suitably shaped to provide static compensation of the estimated average ISS pitch bias (tilted 7 deg) and maximise the SAGE III field of view.

The other important constituent of the HMA is the off-loading device installed around the hexapod mechanism to interconnect the upper platform and the ExPA during launch. It enables the linear actuators to be protected from launch loads, thereby preserving their high accuracy for supporting the scientific mission. The off-loading device will only be disconnected once the Hexapod is in place on the ISS truss, after which the simultaneous activation of all six linear actuators will put the upper platform into its nominal operating position. The Hexapod's ability to control linear translations according to pre-defined trajectories enables the design and operation of the separation device to be simplified considerably.

Hexapod-based positioning/pointing systems are able to achieve pointing in a particular direction via a very large set of possible combinations of the six linear actuator lengths. This provides the ability to recover partially from linear actuator failures by adjusting the pointing algorithms to take into account the actual length of the faulty leg(s), and to continue to execute pointing manoeuvres using only the fully functional legs.

The electromechanical linear actuator (Fig. 3) is a key element in the hexapod mechanism. It has to guarantee a positioning accuracy of better than ±25 micron over the full pointing stroke, with a minimum resolution of 10 micron and a positioning repeatability of better than ±5 micron. The lengths of the linear actuators can range from the fully-retracted minimum of 471 mm, including the two cardan joints, to the maximum stroke length of 568 mm. Their nominal length, corresponding to the 'zero' reference position of the upper platform, is 528 mm.

A DC three-phase brushless motor is installed in direct-drive frameless configuration inside the linear actuator. The stator is installed inside the motor cage, and the rotor is installed on the satellite screw shaft. The motor is double wound for cold redundancy, with the phase commutation provided by two sets of three Hall sensors (one set for each winding). The motor can provide a continuous torque of 0.7 Nm up to 150 rpm, and a peak torque of 1.4 Nm.

Figure 3. The electro-mechanical linear actuator

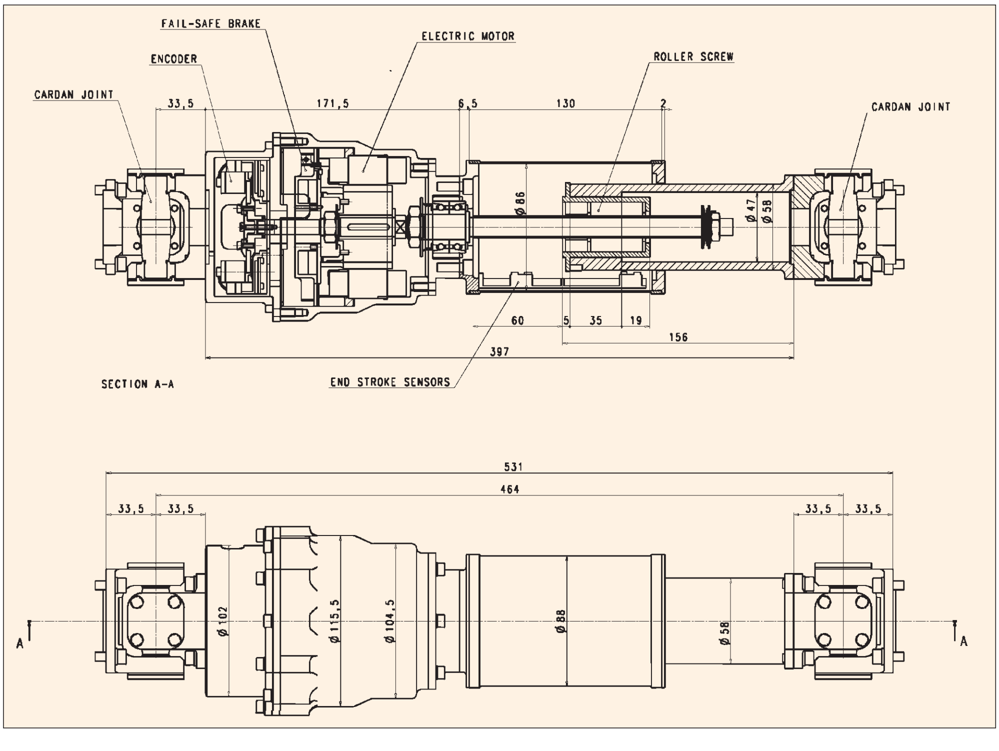


Figure 4. The Hexapod high-fidelity mechanical-interface simulator

A brake is used to lock the rotor, preventing the satellite roller screw back-driving during the re-entry phase. Based on two steel-toothed rings (each with 200 teeth), the brake has two separate solenoid windings (main and redundant), each of which when energised is able to disengage the toothed rings (they are automatically engaged when power is off). The brake system, the materials of which have been specially selected to avoid debris production during engagement/disengagement, is dimensioned to resist a torque of at least 6.3 Nm.

Hexapod ground models

Three Hexapod ground models are deliverable items to support NASA LaRC in its role as integrator of the payload system. The High-Fidelity Avionics Interface Simulator reproduces the hardware and software serial interface to SAGE III. The High-Fidelity Mechanical Interface Simulator (Fig. 4) is an exact mock-up of the essential items of the flight unit as far as overall dimensions, placement of hardware on the lower and upper platforms, and hole locations are concerned. This simulator is used for verifying that the SAGE III sensor assembly mounts properly to Hexapod, and to support payload system integration. The Engineering Unit (Fig. 5) supports sustaining-engineering functions such as anomaly resolution (hardware and software), software modifications, and on-ground verification of system changes during in-orbit operation.

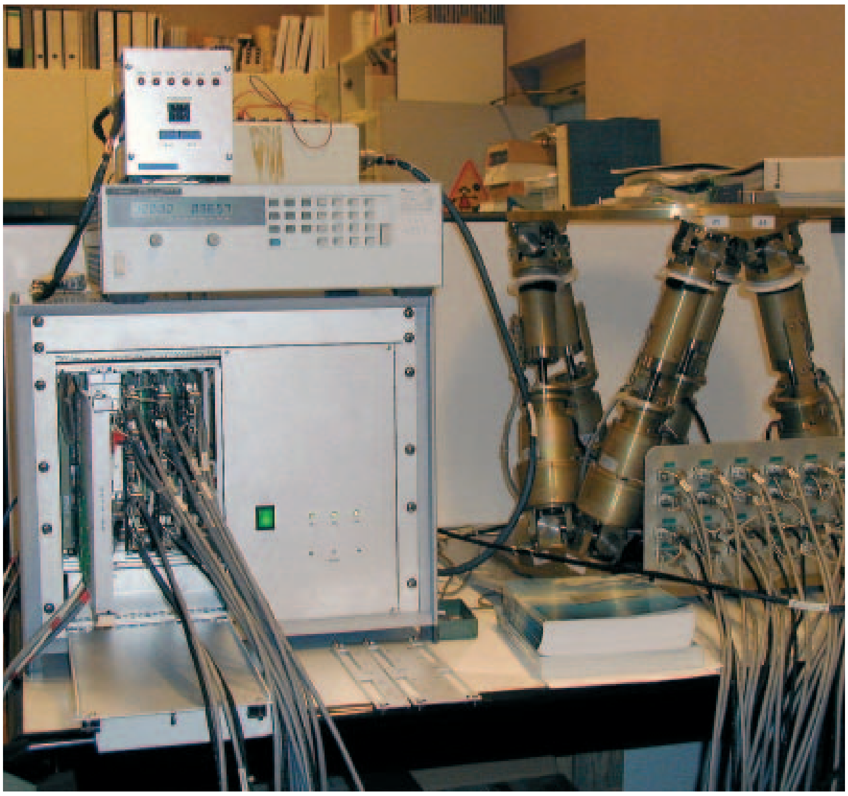


Figure 5. Functional testing of the Hexapod Engineering Unit

Future perspectives

ESA's development of the Hexapod marks the upgrading of hexapod-based positioning/pointing systems for space application. Although tailored to meet the SAGE III nadir-pointing requirements, it can be adapted to support other ISS external payloads, or payloads to be flown on different spacecraft carriers. Feasibility studies conducted before starting the Hexapod design phase indicated the possibility of using them for space applications requiring pointing within about ±30° cones. A target-tracking capability (not requested by SAGE III) can also be provided. The possibility to control payload attitude/position in six degrees of freedom is another attractive feature that could serve a number of space applications in which the relative displacement of two items has to be controlled with high accuracy.

Other possible applications include active jitter stabilisation at the payload interface, operating Hexapod as an anti-vibration platform. A demonstration test performed in 1996 on the Hexapod Phase-B development model indicated that it was able to react 'as-built' to a simulated disturbance by producing an in-phase dynamic response suitable for compensating low-frequency jitter of up to about 2 Hz.

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The authors wish to acknowledge the efforts of all members of the ESA, NASA and Industry (Alenia Spazio and Carlo Gavazzi Space) teams who have contributed to the Hexapod project's success through their dedication and professionalism and in a friendly spirit. Last but not least, very special thanks are due to the late W. Gallieni (ADS Italia), whose innovative ideas and specialist skills were fundamental to the preliminary design-definition phases of the project.