ISS: Columbus

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In 2001, a total of 13 assembly and logistic flights to the ISS were made, using both Russian launchers and the Space Shuttle, including flights of the first European astronauts, payloads and Multi-Purpose Logistics Modules (MPLMs). Several US, Russian and Canadian elements have already been assembled in orbit (Fig. 1) and the fourth Expedition Crew is currently onboard. The cornerstone of ESA's contribution to this enormous international undertaking in space is the Columbus laboratory.

On 27 September 2001, the Columbus flight unit arrived at the premises of ESA's industrial prime contractor Astrium in Bremen, Germany. Final integration of the module is now nearly complete and functional qualification and acceptance testing is about to start. This article summarises the characteristics and functional architecture of Columbus, its development, integration and test approach, as well as today's qualification status.

Introduction

The Columbus laboratory is the cornerstone of ESA's contribution to the International Space Station (ISS; Fig. 2). It is a permanently attached, pressurised laboratory allowing astronauts to work in a comfortable and safe environment (Fig. 3). Columbus will support very sophisticated research in weightlessness for at least 10 years by providing accommodation for experiments in the life and physical sciences, space science, Earth observation, and technology domains.

After completion of the flight-unit mechanical integration phase in Turin, the Pre-integrated Columbus Assembly (PICA) was delivered to the prime contractor's premises in Bremen on

Figure 1. Appearance of the ISS by December 2001. (NASA)

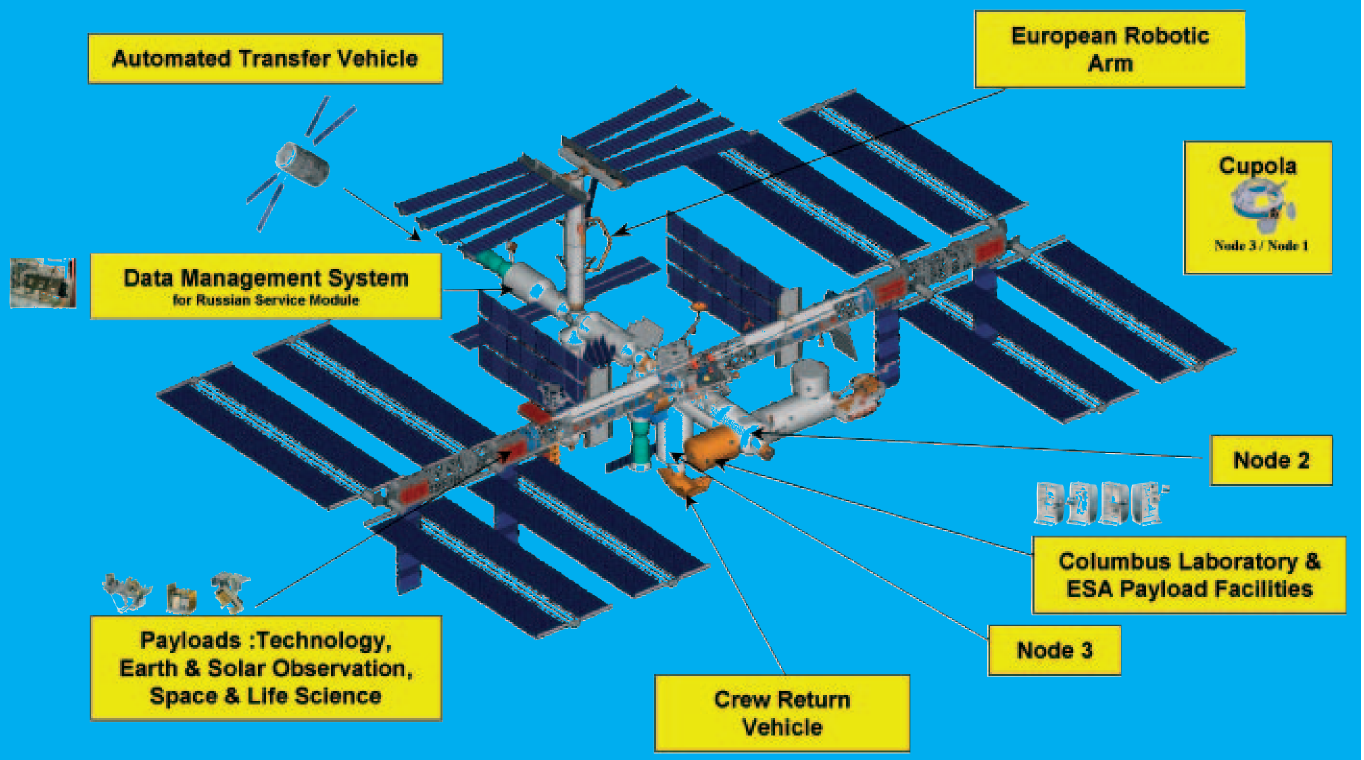

Figure 2. ESA's contributions to the ISS.

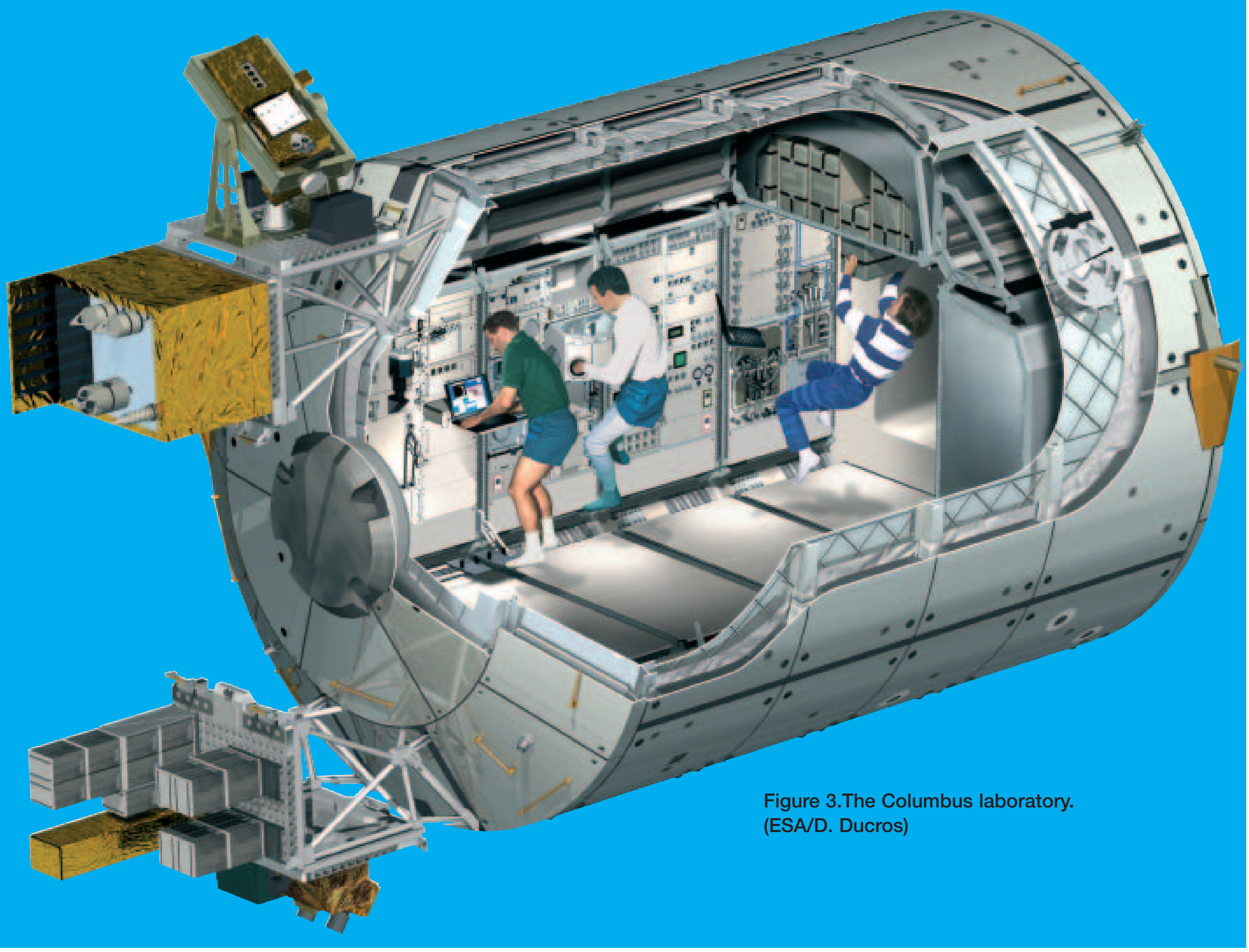

Figure 3.The Columbus laboratory. (ESA/D. Ducros)

27 September 2001 (Figs. 4–6). Flight-unit final integration will be completed by early 2002 and final system functional testing will then start, bringing Columbus a major step closer to being ready for its journey into orbit.

Columbus characteristics

The purpose of Columbus is to support experiments and payload operations once attached to the International Space Station. It therefore provides internal payload accommodation. In addition, the External Payload Facility (EPF) provides four payload platforms for experiments, which are directly exposed to space. Although it is physically the Station's smallest laboratory module, it provides the same payload volume, power, data retrieval, vacuum/venting services, etc. as the others (Table 1). This could only be achieved by careful utilisation of the available volume and high equipment packaging density.

The Columbus laboratory has a 4.2 m-diameter cylindrical section closed with welded end-cones, with a total length of 8 m, including the EPF, and weighing about 10.2 t without research equipment. The module has a pressurised habitable volume about 6.1 m long. The laboratory's total volume is about 75 m^3, of which about 25 m^3 is the working habitable volume when all racks are installed. It will be attached to the ESA-provided interconnecting Node-2 via the module's Common Berthing Mechanism (CBM).

Inside Columbus, the laboratory racks are arranged around the circumference of the cylindrical section to provide the working

Figure 4. The Columbus flight unit being unloaded from its Beluga transporter at Bremen airport, on 27 September 2001. The servicer attached to the transport container provided atmospheric control.

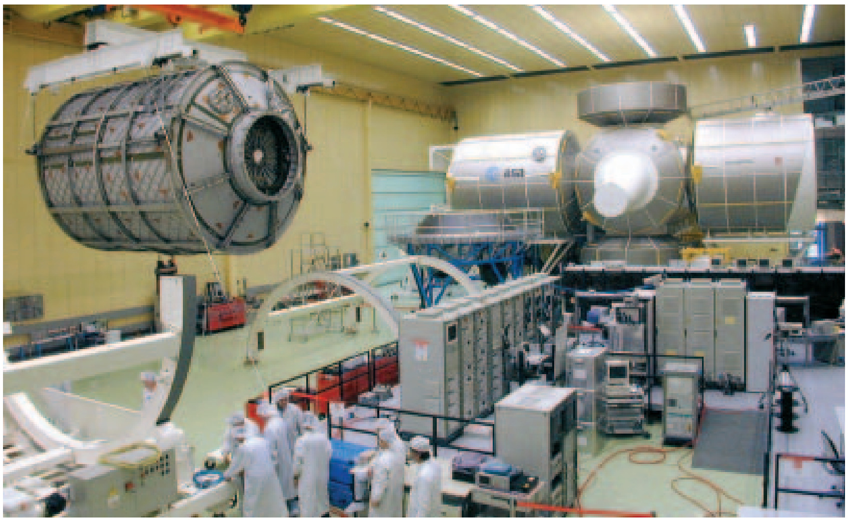

Figure 5. Columbus being moved to its integration stand in the prime contractor's integration hall. The ISS mock-up in the background includes Columbus and the Japanese Experiment Module, both attached to Node-2. The dark cabinets in front of the mock-up are the ETM racks, the lighter ones are the EGSE racks.

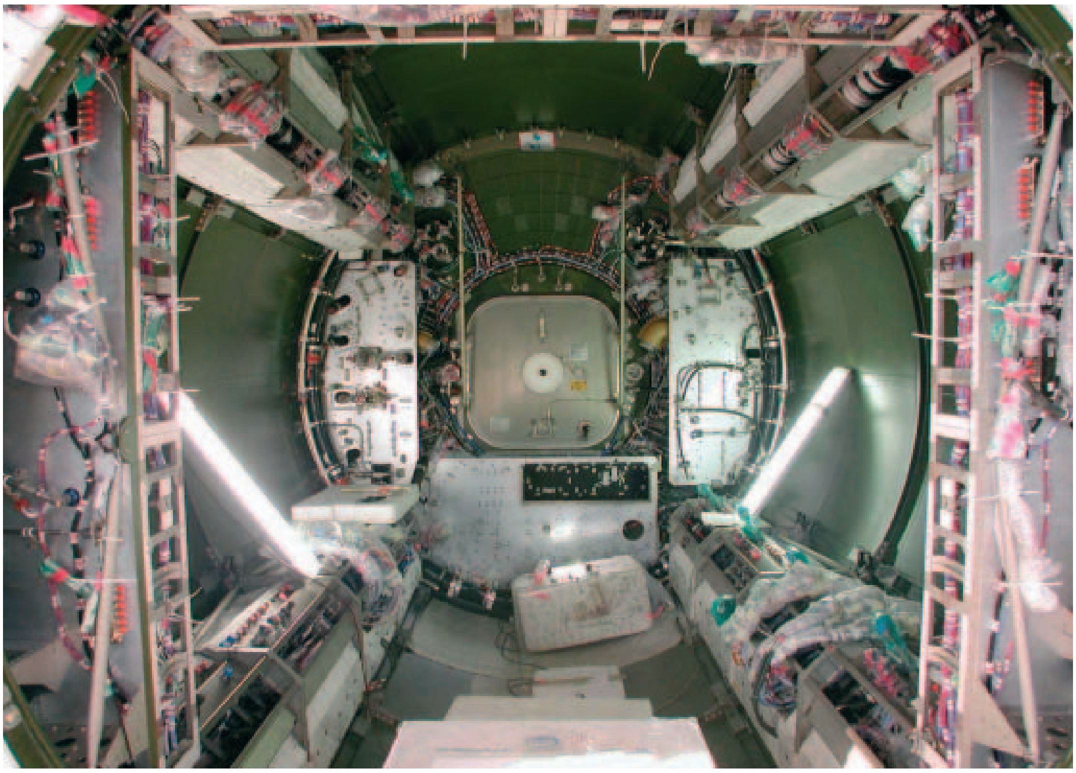

Figure 6. The Columbus interior as completed in Turin.

Table 1. Columbus payload resources

Total Resources	Internal	External	Remarks
Location:	- 10 active ISPRs - 3 Stowage ISPRs - Centre aisle	- 4 interface planes pointing to zenith, nadir & flight direction	8 lateral rack positions support Active Rack Isolation System. Functional resources from Standard Utility Panels.
Mass: - 2500 kg at launch - 10160 kg on-orbit	- 2500 kg at launch - 9000 kg on-orbit	- 0 kg at launch - 4 x 290 kg on-orbit	
Electrical Power: - 13.5 kW total - 120 Vdc	- 5 x 6kW ISPRs - 5 x 3kW ISPRs - 3 x 1.2kW Standard Utility Panels	- 2 x 1.25kW per external payload location	Overall total during mission depends on power availability from ISS. 1.2kW Auxiliary Power also available for each rack.
Cooling:	- 1 water cooling loop per active ISPR	- Passive cooling	
Data Management: - 1 dedicated payload computer - Crew interfaces by laptop - Columbus payload bus (MIL-STD-1553) - US payload bus (MIL-STD-1553) - Columbus Local Area Network (Ethernet) - American Local Area Network (Ethernet)	- 1 cold redundant per ISPR - 1 cold redundant per active ISPR - 1 cold redundant per active ISPR - 1 cold redundant per active ISPR	- 1 cold redundant per interface plane for Columbus or American bus - 1 cold redundant per interface plane for Columbus or American Local Area Network - Analogue/discrete inputs/outputs	- Telemetry and telecommand links to/from ground via ISS S-band systems - For monitoring and control of external payloads, and commanding of ISPRs
Video: - Video distribution (National Television System Committee), compression (Motion Picture Experts Group) and transmission to ground - Video recording - Video monitoring - Video cameras	- 2 interfaces per active ISPR	- N/A	either for video or high-rate data transmission.
Data: - Multiplexing and downlink (up to 43 Mbits/s via Space Station Manned Base and/ or Japanese Experiment Module - in steps of 0.5 Mbps) **High Rate Data:** - 2 Fibre Optic directly connected to the Space Station Manned Base (each active rack location) for high rate data transmission (generally used by American racks)	- 2 interfaces per active ISPR	- 2 cold redundant per interface plane	- Fibre optics interface at ISPR, electrical interface at the Columbus External Payload Facility.
Vacuum & Venting: - Vacuum line - Venting line	- 1 per lateral ISPR (x8) - 1 per active ISPR (x10)	- N/A - N/A	- $< 2.28 \times 10^{-6}$ bar
Nitrogen Supply:	- 1 per active ISPR (x10)	- N/A	

ISPR: International Standard Payload Rack N/A: not applicable

environment for up to three astronauts. A total of 13 racks are available for payloads, of which 10 are completely outfitted with payload resources and 3 provide passive stowage accommodation. System equipment that requires undisturbed crew viewing and handling access, such as video monitors and cameras, switching panels, audio terminals and fire extinguishers, is located on the starboard cone. The remainder of the system equipment is housed in the rest of the end-cone areas and in three of the deck (floor) racks.

Columbus will be carried to the ISS by the Space Shuttle Orbiter. A Station-common grapple fixture will allow the Station's Remote Manipulator System (SSRMS) to lift Columbus out of the Shuttle Orbiter and attach it at its final location on ISS Node-2. Columbus will be launched with up to 2500 kg of payload already in place in its payload racks, which will be complemented and/or reconfigured in orbit by later launches of additional racks. The external payloads will be installed in orbit, using the SSRMS, as standardised packages interfacing with the External Payload Facility.

Functional architecture

Columbus is a manned laboratory and is therefore equipped with an Environmental Control and Life Support (ECLS) subsystem, as well as man/machine interface provisions. Air circulation fans continuously take fresh air from Node-2, pass it into the crew cabin for ventilation and then back to the Node for refreshing and carbon-dioxide removal. Air content is monitored for contamination from the systems or payloads. The Columbus active thermal control is via a water loop, connected to the ISS centralised heat-rejection system via interloop heat exchangers. An additional air/water heat exchanger removes condensation from the cabin air. The crew can control both temperature and humidity.

All safety-related parameters of the system and payloads are monitored and controlled by a redundant set of computers (VTCs), which alert the Station in the event of a problem occurring onboard Columbus. Both audio and visual warnings are given to the crew, and laptop interfaces allow the astronauts to 'safe' the module from any location in the Station via the ISS command and control data bus.

Non-safety-related system and payload data are generated and distributed by the Columbus Data Management System (DMS) – a series of computers and other electronic equipment, connected to the data busses and Ethernet local-area network. The DMS is the basis of the Columbus onboard software. It is extended by laptop applications and automated flight procedures to provide end-to-end system functions.

As mentioned earlier, the crew interfaces via laptops, which can be plugged into the system at many locations inside the Station.

Power for the complete Station is generated centrally by large solar wings and routed to all Station users. Inside Columbus, the power goes through the Power Distribution Unit (PDU) and from there to all payload racks, external platform locations, centre-aisle standard utility panels and subsystems.

All data collected onboard Columbus, including housekeeping, low- and high-rate payload and video data, are multiplexed and then routed through the Station to the ground control centres, either via NASA's Tracking & Data Relay Satellite System (TDRSS) or the Japanese Experiment Module and related links.

The Columbus Control Centre, a facility at the German Space Operations Centre (GSOC) in Oberpfaffenhofen, further transmits the data to de-centralised User Centres, which will have direct access to the payloads under their responsibility. In addition to handling the command and control of the module, the Columbus Control Centre will coordinate the planning and timelining of all Columbus orbital activities and will provide the real-time operational decision making.

Columbus development, integration and testing

The Columbus development, integration and test programme has a hybrid approach. The classical project review system of design, qualification and acceptance reviews are based on lower level reviews. The model philosophy at the unit level ranges from dedicated qualification units to the protoflight approach, depending on the complexity of the items. Several units common to other projects have been adopted without further qualification, after demonstration that they meet or exceed the Columbus requirements. Qualification of commercial equipment required more stringent environmental criteria to compensate for the uncertainties of the reduced design and manufacturing transparency.

A system-level engineering model as such does not exist. Columbus functional qualification is performed on the Electrical Test Model (ETM) and/or on the Protoflight Model (PFM), supplemented by analyses and best demonstrations on various mock-ups:

Electrical Test Model

The ETM is functionally identical to the Columbus flight unit for avionics and software items, and includes the complete power-distribution and data-management system. All avionics units are represented by their engineering models. These are identical to the flight models in terms of physical and functional design, differing only in their detailed manufacturing processes and parts quality. A dynamic simulation of the liquid-cooling and cabin-air loops complements the functionality of the ETM. The latter does not contain representative primary or secondary structures, and does not represent the module physically, but includes a fully representative set of power equipment and data harnesses, which are mounted in standard racks for easy access, and all onboard software.

The other Columbus system items are simulated, so that all system functions can be exercised and used for troubleshooting in parallel with the flight-model assembly, integration and test. In order to ensure end-to-end testing, the ETM is functionally attached to specific Ground Support Equipment (GSE), which simulates the ISS and payload-interface provisions.

After completion of the ETM testing, the model will be extended to become the Rack Level Test Facility (RLTF), by adding flight-identical mechanical and thermal interfaces and thereby providing all of the features required to test the payload interfaces under realistic conditions. Any future payload complement can then also be tested during the lifetime of Columbus to generate a realistic in-orbit operating scenario for the payload under test. For those payloads that will be launched within Columbus, this testing will be done before their integration into the Columbus flight configuration.

Protoflight Model

All remaining functional qualification activities that could not be performed on the Columbus ETM will be performed on the PFM. These include those requirements that need the complete physical system configuration, such as electromagnetic susceptibility, internal noise, microgravity disturbance and overall contamination levels.

Mock-ups

Mechanical mock-ups of relevant parts of the module were used in the early stages of the programme to assess several aspects of the laboratory's design, including its accessibility and maintainability (1g mock-up demonstrations). Later in the programme, a complete Columbus 'zero-gravity' mock-up has been used to verify in-orbit maintenance procedures, such as the replacement of functional units and local repair of the structure and harness, both from inside and outside the module, while complying with specific ergonomic and human-factor requirements.

Structure

Structural launch environment qualification has been achieved by analytical extrapolation of the full-scale tests performed on the ASI MPLM, from which the Columbus primary structure was derived. This analysis has been backed-up by a dedicated Columbus modal-survey test.

Training

In order to support the training of all ISS astronauts for Columbus throughout its operational phase, the Columbus Crew Trainer has been developed. Mechanically speaking, it represents the physical interior of Columbus and simulates its functional characteristics. One Crew Trainer is now at the European Astronaut Centre (EAC) in Cologne, and a second one forms part of the Space Station Training Facility (SSTF) at NASA's Johnson Space Center (NASA/JSC) in Houston.

A facility simulating the complete ISS onboard avionics system for trouble-shooting and change evaluation (e.g. software upgrades) across all element interfaces during the Station's operational phase is available at NASA/JSC. This facility is being extended as new elements are attached on board the ISS. The Columbus Software Verification Facility (SVF) is a functional simulator, which is being developed for integration into this overall ISS simulation facility.

Flight-unit integration and qualification

Following the successful Columbus Critical Design Review (CDR) in December 2000, flight-unit assembly, integration and test was released. Several requirements had already been verified by then, among which were the following:

- Cabin ventilation was verified in February 1999 on a mock-up of the Columbus interior, using the fans and ducting hardware.
- Fire-suppression qualification tests were conducted in March 1999 on mechanical mock-ups of the relevant areas.
- The environmental- and thermal-control systems were qualified in 1999 and 2000, using a fluid-loop breadboard equipped with the engineering models of the related assemblies.
- A mechanical mock-up was used at Alenia in Turin (I) to demonstrate and qualify in-orbit maintenance procedures under 1g. Another mock-up was used for the first zero-gravity verification of internal operations, which was performed in a water tank at Alenia with the support of ESA and NASA astronauts. They also supported the final zero-gravity verification of external operations, including ergonomics and human-factor requirements verification, performed in 2000 at the Neutral Buoyancy Laboratory at NASA/JSC (Fig. 7), which demonstrated the ability to perform Extra Vehicular Activity (EVA) servicing.

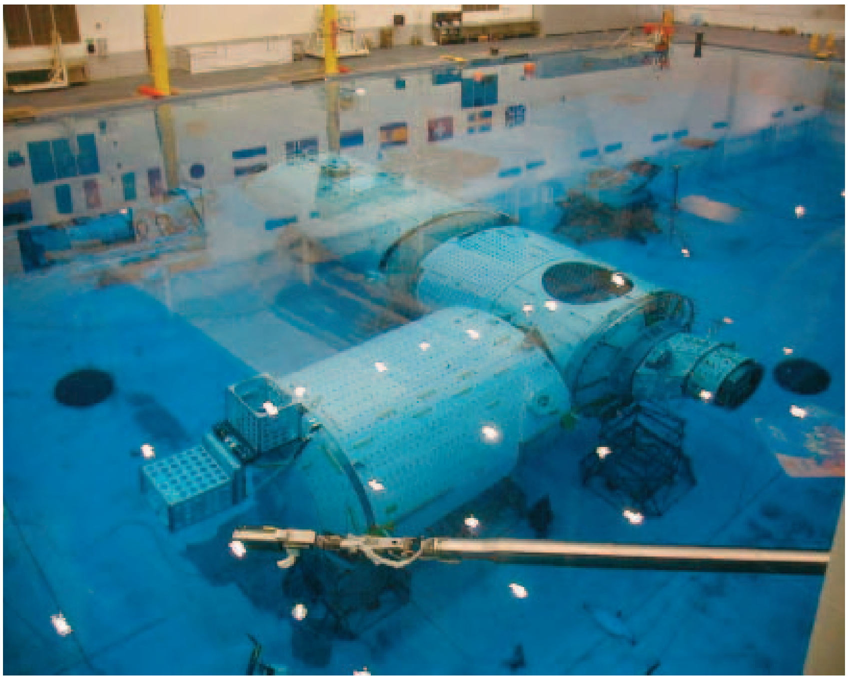

Figure 7. Columbus mock-up attached to Node-2 mock-up in the pool of NASA/JSC's Neutral Buoyancy Laboratory, where zero-gravity verification of external operations (EVA) has been performed. (NASA)

– The primary and secondary structures had been qualified in 2000 by pressure/leakage and modal-survey tests to verify pressure integrity requirements, as well as the finite-element model.
– Tests performed continuously on the ETM in Bremen helped to identify early and to resolve any compatibility problems and deficiencies.
– The first test jointly performed with NASA and the ISS prime contractor Boeing on data-communications exchange between Columbus and the rest of the ISS was successfully completed in June 2001.

The Columbus flight-unit integration began at Alenia Spazio's premises in Turin in March 2001 with the integration of the PICA (pre-integration phase), which comprises all mechanical items, such as:
– primary and secondary structures
– thermal-control system (TCS) and environmental control & life-support system (ECLS) equipment
– harness, ducting and plumbing
– illumination, crew support equipment, and
– external protection like multi-layer insulation and micrometeoroid and debris-protection items.

With the delivery of the Pre-integrated Columbus Assembly (PICA) on 27 September 2001 to Astrium's premises in Bremen, a major milestone in the development of the Columbus laboratory was achieved. Flight-unit final integration has started there, with Astrium currently integrating all functional elements into the Columbus module, including:
– power distribution units
– communications equipment (including video and audio communication)
– data-management equipment, and
– flight-application software.

The Columbus module will then be ready for functional qualification and acceptance testing, once the module's ISS interfaces have been attached to the relevant ground-support equipment:
– Electrical Ground-Support Equipment (EGSE) will provide resources for power and data exchange.
– Fluid and Gas Support Equipment (FGSE) will provide basic resources for cooling, gas and air supply.

The flight model of Columbus is planned to be powered-up for the first time in February 2002.

The ETM test campaign has been underway for over a year and will continue in parallel with the PFM test campaign. The following tests will be executed on the flight model:
– All system functions, including activation/ deactivation of the subsystems.
– Hardware/software compatibility test, which will require the greatest effort. This test will include certification of the Mission Database contents, which includes onboard and ground software and all data used to configure the software, such as sensor information, command definition, downlink telemetry packet definition and event messages.
– Mission simulation test, which will require a similar effort in operating the system under flight-operations conditions.
– All systems will be verified for compliance with the specified electromagnetic environment.
– Several tests will be performed jointly with NASA and the ISS prime contractor Boeing to ensure full ISS compatibility.
– System tests for thermal and environmental control, audible noise and microgravity attenuation, offgassing characterisation of the module's interior, and illumination of the crew compartment.

A particular feature of the Columbus development programme is the involvement of ESA astronauts as part of the project team. Pedro Duque has been a member of the design team for several years, participating in the Critical Design Review, Neutral Buoyancy Test, mock-up demonstrations and functional tests. Thomas Reiter is co-located in Bremen for familiarity training. Their involvement has resulted in a design that should be crew-friendly, and provides productive on-the-job training for the astronauts involved.

Conclusion
Acceptance of the Columbus laboratory flight model from the prime contractor will take place in two steps. The first step is to certify that the Columbus system meets its system requirements, including external interface requirements, without the payload facilities having been integrated. The second step is to authorise shipment of the integrated Columbus, including payloads, to the launch site in Florida, once the payload facilities have been installed and successfully tested for compatibility with the module. Columbus will then be shipped to NASA's Kennedy Space Centre (KSC) for pre-launch processing. Final acceptance for flight will be achieved in conjunction with the NASA ISS and Shuttle programmes, and will include confirmation of the readiness of the associated Ground Segment, including the Columbus Control Centre.

The Columbus laboratory's launch is currently scheduled for October 2004.


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