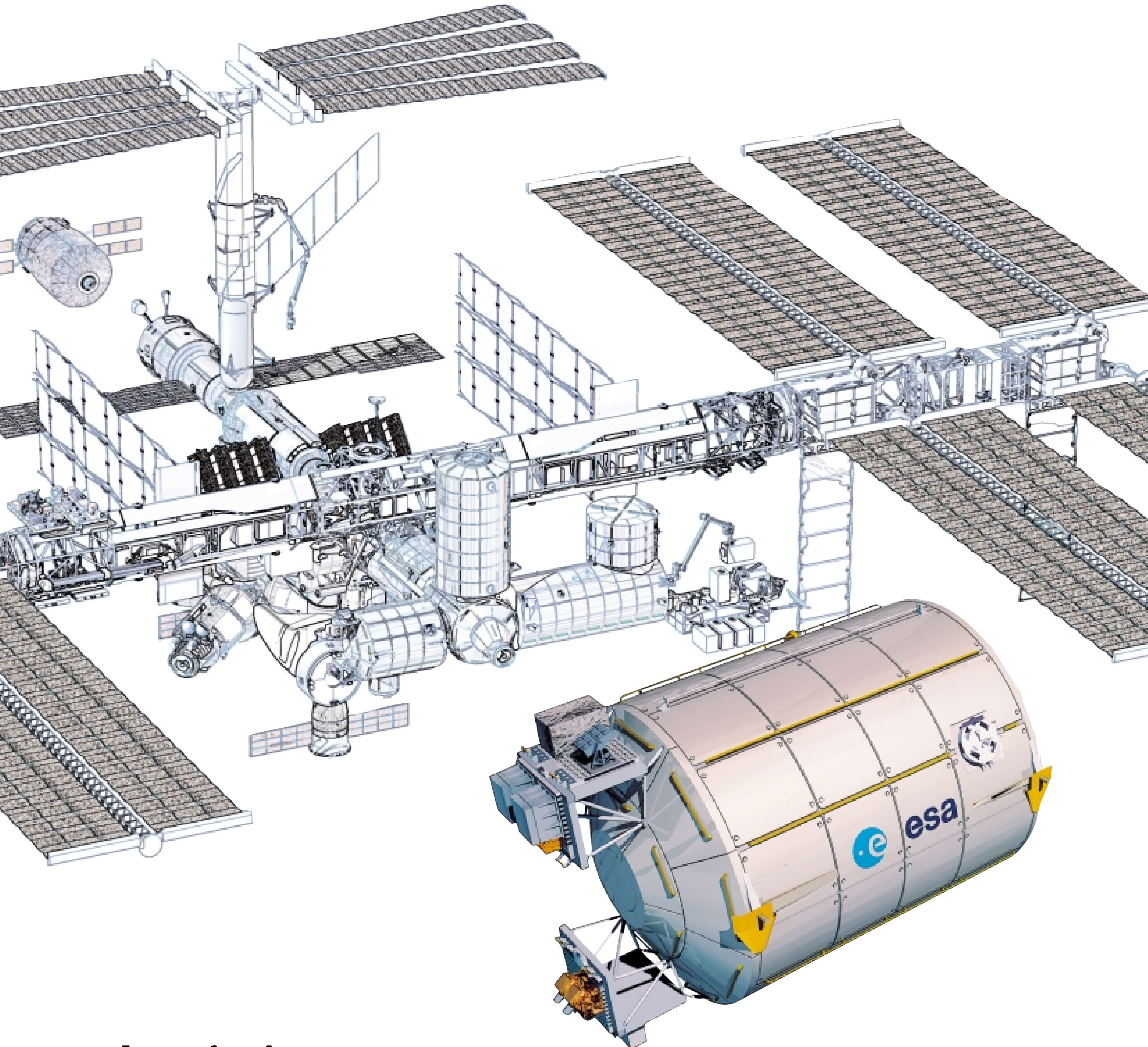
BR-144

October 1999

Columbus: Europe's Laboratory on the International Space Station



European Space Agency
Agence spatiale européenne

Directorate of Manned Spaceflight and Microgravity
Direction des Vols Habités et de la Microgravité

BR-144
October 1999

Columbus:

Europe's Laboratory on the International Space Station

European Space Agency
Agence spatiale européenne

Directorate of Manned Spaceflight and Microgravity
Direction des Vols Habités et de la Microgravité

Contents

Further information on ESA and its participation in the International Space Station can be found at http://www.estec.esa.nl/spaceflight/

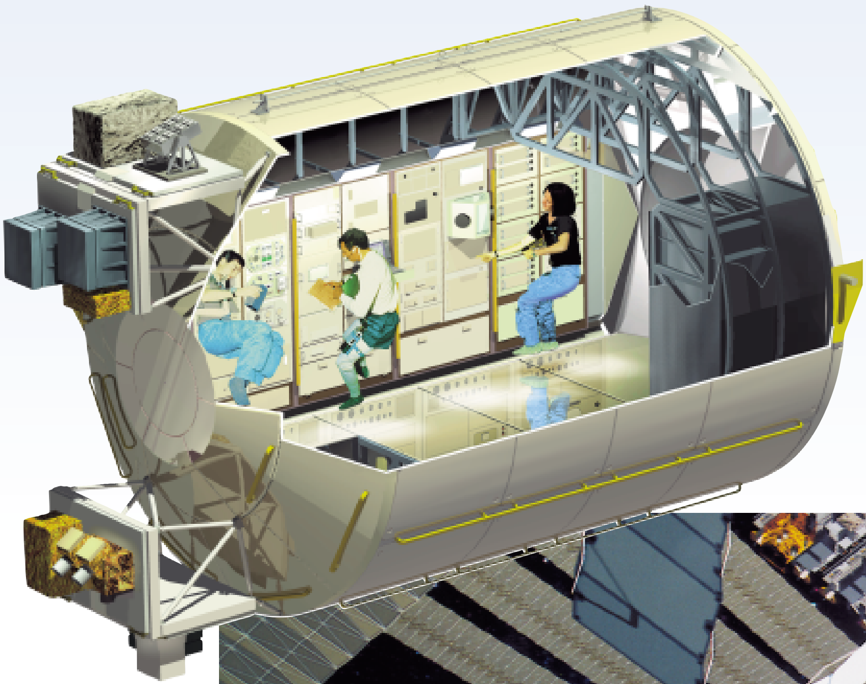


Fig. 1a. ESA's Columbus module is a general-purpose laboratory. (ESA/D. Ducros)

Fig. 1a. The International Space Station as it will appear after completion in 2004. (ESA/D. Ducros)

In the Beginning...

In October 1995, at their meeting in Toulouse, the ESA Council met at Ministerial level and approved the programme 'European Participation in the International Space Station Alpha' – some 10 years after the authorisation of studies and Phase B work by the Ministerial Council at Den Haag in 1985. During that 10-year period, a variety of flight elements and associated ground infrastructure was studied and developed in parallel with coherent work on the Ariane-5 and Hermes programmes, which all led to integrated European scenarios that were clearly unaffordable. Therefore, in late 1994, a series of dramatic programmatic cutbacks was introduced, which underwent frequent iterations with ESA Member States and the Space Station Partners, in particular the US. The process culminated in a package worth some EUR2.6 billion being approved in Toulouse.

This approved programme consisted of:

- the Columbus laboratory development and launch (at that time called the Columbus Orbital Facility, or COF, but now simply Columbus, Fig. 1a), a module permanently attached to the International Space Station (Fig. 1b) for conducting scientific experiments, research and development;

- the Automated Transfer Vehicle (ATV), a logistics vehicle launched by Ariane-5 for uploading research and system equipment, gases and propellant, and the destructive downloading of Station trash;

- Station utilisation preparation and astronaut-related activities;

Europe and the International Space Station

European involvement in manned spaceflight stretches back to 1969, when NASA issued an invitation to participate in the post-Apollo programme. Europe opted in 1972 to develop the modular Spacelab as an integral element of the Space Shuttle. Spacelab's 22 missions between November 1983 and April 1998 made outstanding contributions to astronomy, life sciences, atmospheric physics, Earth observation and materials science.

Participation in the International Space Station now takes Europe to the front rank of manned space flight. For the first time, more than 40 years after the dawn of the Space Age, scientists and engineers will maintain a permanent international presence in space. While orbiting at an average altitude of 400 km, they will continuously perform scientific and technological tests using laboratories comparable with the best on Earth. The Station will be a research base like those built in the Antarctic, but it uniquely involves five international Partners (USA, Europe, Japan, Russia and Canada) and embraces most fields of science and technology.

Physicists, engineers, physicians and biologists will work together pursuing fundamental research and seeking commercially-oriented applications. Research will extend far beyond fundamental goals such as puzzling over the mysteries of life: the Station will be a test centre for developing innovative technologies and processes, speeding their introduction into all areas of our lives.

Fully assembled after 5 years, the International Space Station will total about 420 t in orbit and offer 1300 m^3 of habitable volume. With a length of 108 m, span of 74 m and vast solar panels, it will shelter a permanent crew of three astronauts during the assembly phase and 6-7 once it becomes fully operational in 2004. There will be six laboratories. The US will provide one plus a habitation module; there will be European, Japanese and Russian research modules, all maintained with Earth-like atmospheres. Additional research facilities will be available in the connecting Nodes. The central 90 m Truss connecting the modules and the main solar power arrays will also carry Canada's 17 m-long Remote Manipulator System robot arm on a mobile base to perform assembly and maintenance work. An emergency crew return vehicle – initially a Russian Soyuz and later a Crew Return Vehicle (with ESA involvement) – will always be docked once permanent habitation begins in early 2000.

ESA's major contribution to the Station is the Columbus laboratory. Columbus will provide Europe with experience of continuous exploitation of an orbital facility, operated from its own ground control facility in Oberpfaffenhofen, Germany. In this pressurised laboratory, European astronauts and their international counterparts can work in a comfortable shirtsleeve environment. This state-of-the-art workplace, launched in early 2004, will support the most sophisticated research in weightlessness for at least 10 years. Columbus is designed as a general-purpose laboratory, accommodating astronauts and experiments studying life sciences, materials processes, technology development, fluid sciences, fundamental physics and other disciplines.

- studies of a European Crew Transport Vehicle (CTV), leading to involvement in the X-38 demonstrator and possible participation in the Crew Return Vehicle (CRV);

- exploitation of the results of the Atmospheric Reentry Demonstrator (developed under the Hermes programme) for ATV and CTV.

The ISS consists of pressurised and unpressurised elements, including:

- laboratory modules from the US, ESA, Japan and Russia;

- a robotic manipulator system from the Canadian Space Agency;

- interconnecting Nodes and crew habitation quarters;

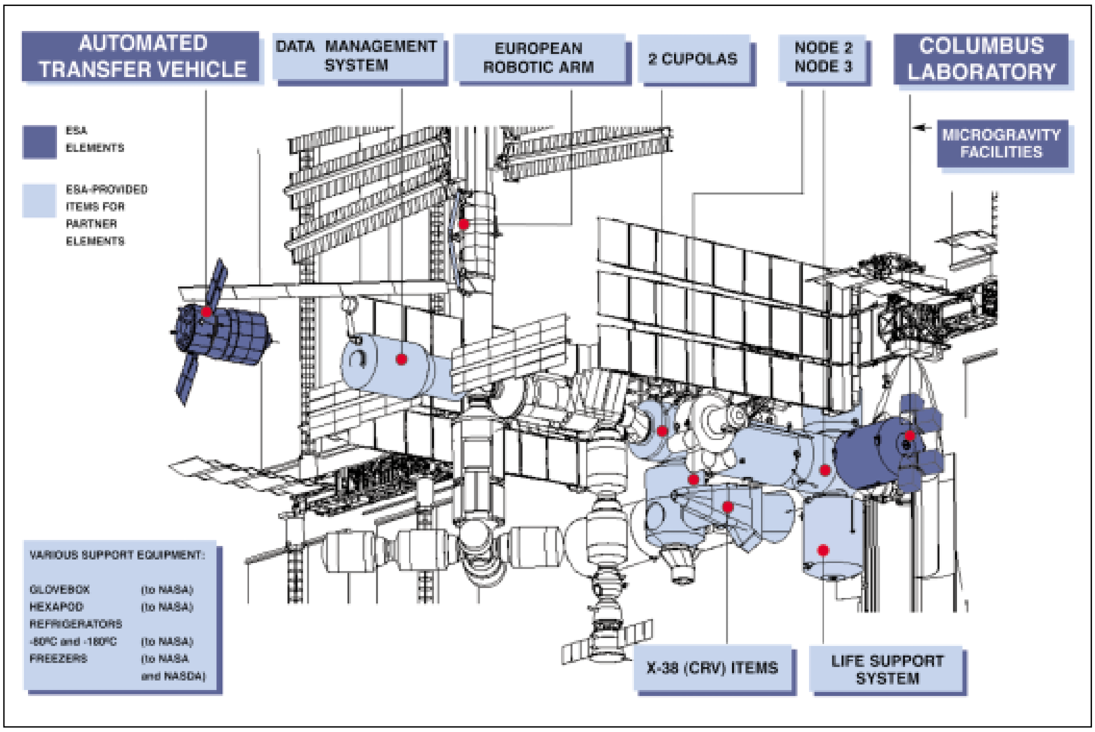
- a service module, a control module, docking modules and an airlock;

- crew transfer and crew rescue vehicles;

- truss structures supporting solar generators, radiators and exposed payload platforms.

After initial assembly, the Station will be permanently manned by up to seven crew members drawn from all five of the Partners. Assembly began at the end of 1998 and is planned for completion in 2004.

Fig. 2. Europe's contribution to the International Space Station. The main elements – Columbus, ATV and the microgravity facilities – are in dark blue. (ESA)



The Columbus laboratory is the cornerstone of Europe's participation in this enormous international undertaking. It will be positioned on the starboard side of the Station's leading edge.

Following quickly after the Toulouse Ministerial conference, a contract was signed between ESA and its Prime Contractor, Daimler Benz Aerospace (now DaimlerChrysler Aerospace), DASA, in March 1996, at a fixed price of EUR658 million, the largest single contract ever awarded by the Agency at that time. DASA heads a consortium of contractors reflecting the cream of Europe's industrial expertise in manned space, developed as a result of the Spacelab programme, and which will be described in more detail later in this brochure.

ESA's Exploitation Programme for 2000-2013 was presented at the Ministerial Council meeting in Brussels in May 1999, where the overall programme approach and the initial phase of activities were approved. The programme will be carried out in 5-year phases, each with a 3-year firm commitment and a 2-year provisional commitment. The programme covers the System Operations costs in Europe, the ESA share of the overall Station Common Operations costs and the European Utilisation-related costs. The average yearly cost over the whole period will be about EUR280 million, in 1998 economic conditions.

This brochure describes the characteristics of the Columbus laboratory, its development philosophy and status, the utilisation plans, the industrial development team, ground segment development and astronaut training, the status of overall Station assembly and the immediate future for Columbus.

Columbus Characteristics

Payload Accommodation and Resources

Columbus, in common with the rest of the International Space Station, provides an environment for pursuing research and applications development in many fields. It offers unique fundamental characteristics:

- payload complement flexibility, provided by a modular design serviced by a regular logistics, maintenance and upgrade capability;

- permanent crew presence, for servicing payload-support systems and interacting with the payloads;

- continuous availability of a ground infrastructure for monitoring and controlling onboard activities, with the decentralised approach allowing experimenters to interact with their payloads.

Columbus provides internal payload accommodation for multidisciplinary research into material science, fluid physics and life sciences – all requiring minimum microgravity disturbances. In addition, the External Payload Facility (EPF) hosts space science and Earth observation payloads. Although it is the Station's smallest laboratory module, Columbus offers the same payload volume, power, data retrieval, vacuum/venting services, etc as the others. This is achieved by careful utilisation of the available volume and by sometimes compromising crew access and maintainability in favour of payload accommodation.

All of the Columbus payload accommodation locations provide a multitude of resources (see Table 1) so that a wide spectrum of payloads can be handled for the many years of operations to come.

System functions such as Emergency, Warning & Caution detection and annunciation, voice communication to/from the ground and internal monitoring by two video cameras have interface provisions for payloads. In general, the payload interfaces are designed so that failures cannot propagate from the payload hardware to the Columbus system, and vice versa. For example, if the system water pump fails, the DMS automatically reconfigures to the backup pump, so that the payload racks are not left without cooling.

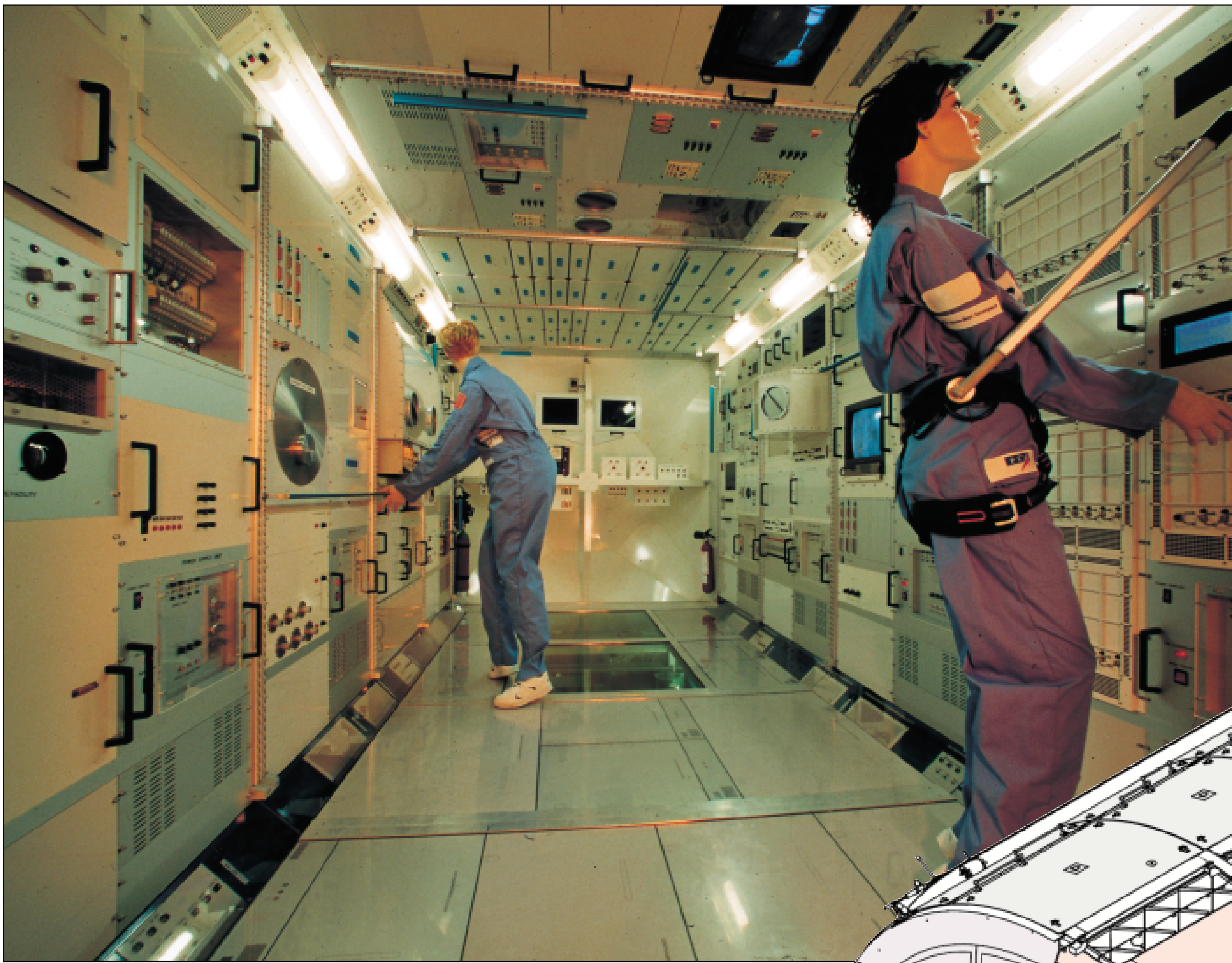
The International Standard Payload Racks (ISPRs) carry standardised interfaces that allow integration and operation in any non-Russian ISS module, including Columbus. European payloads are connected to dedicated data busses, enabling data to be routed, via the ISS data transfer system, directly to the European Control Centre and thence to the individual users, in a secure environment. For payloads in NASA racks, interfaces to the NASA Data Management System are provided.

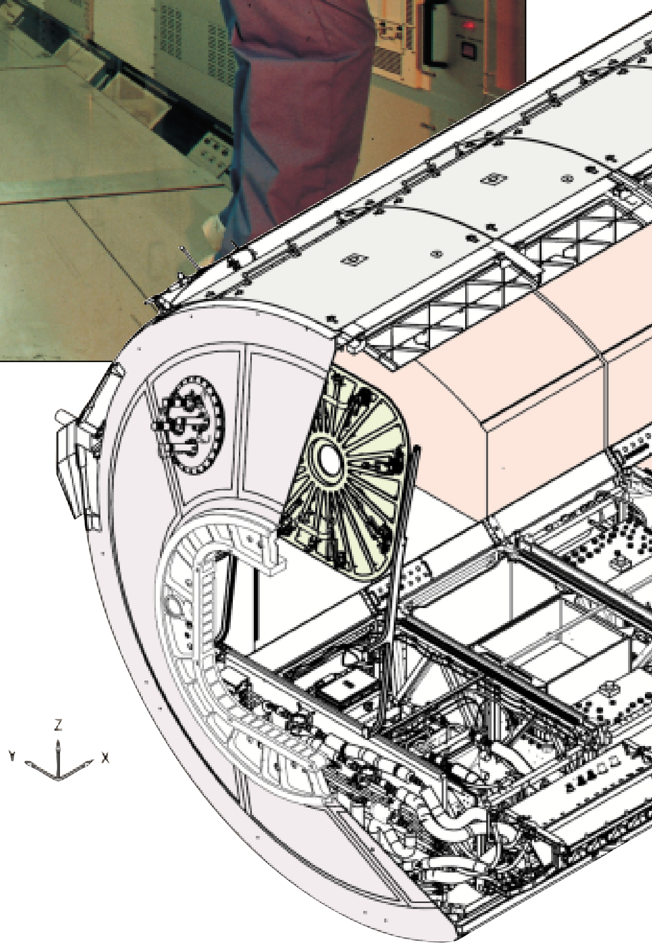
Columbus will be launched with an internal payload of up to 2500 kg in five racks, which will be completed and/or reconfigured on-orbit by later launches of additional ISPRs. The external payloads will be installed on-orbit using the Space Station Remote Manipulator System (SSRMS) as standardised packages interfacing with the External Payload Facility.

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 (ARIS). 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 ▪ 4x290 kg on-orbit	
Electrical Power ▪ 13.5 kW total ▪ 120 Vdc	▪ 5x6 kW ISPRs 5x3 kW ISPRs 3x1.2 kW Standard Utility Panels	▪ 2x1.25 kW per interface plane	Overall total during mission depends on power availability from ISS. Additional 1.2 kW Auxiliary Power also available for each rack.
Cooling	▪ 1 water cooling loop per active ISPR	▪ passive cooling	
Data Management ▪ 1 dedicated payload computer (SPARC) ▪ Crew interfaces by laptop ▪ Columbus payload bus (MIL Std 1553)	▪ 1 cold redundant per active ISPR	▪ 1 cold redundant per interface plane for Columbus or US bus	Telemetry & telecommand links to/ from ground via ISS S-band systems
▪ US payload bus (MIL Std 1553)	▪ 1 cold redundant per active ISPR	▪ 1 cold redundant per interface plane for Columbus or US LAN	
▪ Columbus LAN (ETHERNET)	▪ 1 cold redundant per active ISPR	▪ Analog/discrete inputs/ outputs	For monitoring and control of of external payloads.
▪ US LAN (ETHERNET)	▪ 1 cold redundant per active ISPR		
Video ▪ Video distribution (NTSC), compression (MPEG) and transmission to ground ▪ Video recording	▪ 2 interfaces per active ISPR	▪ N/A	Fibre optics interface either for video or high-rate data transmission.
High-Rate Data ▪ Multiplexing and downlink (up to 43 Mbit/s via SSMB and/or JEM)	▪ 2 interfaces per active ISPR (1 kbit/s up to 32 Mbit/s)	▪ 2 cold redundant per interface plane (1 kbit/s up to 32 Mbit/s)	Fibre optics interface at ISPR, electrical at EPF
Vacuum Line	▪ 1 per lateral ISPR (8x)	▪ N/A	$<0.19 \times 10^{-6}$ bar
Venting Line	▪ 1 per active ISPR (10x)	▪ N/A	
Nitrogen Supply	▪ 1 per active ISPR (10x)	▪ N/A	

N/A: not applicable





Columbus Physical Characteristics

The Columbus laboratory – 9.9 t without research equipment – has a 4.5 m-diameter cylindrical section closed with welded endcones, forming a pressurised, habitable volume about 8 m long in total. The total volume is about 75 m^{3}., reducing to about 50m^3 with a full rack load. The 2219-aluminium alloy cylinder is 4 mm thick, increasing to 7 mm for the endcones. The module's passive Common Berthing Mechanism (CBM) will attach it to the active CBM of the ESA-provided interconnecting Node-2.

Columbus will be delivered to the ISS by the Space Shuttle Orbiter, carried in the spaceplane's cargo bay via its trunnions and keel fitting. A Station-common grapple fixture will allow the SSRMS to lift it out of the Orbiter and transport it to its final destination on Node-2.

Inside Columbus, the ISPR laboratory racks are arranged around the circumference of the cylindrical section, in a 1 *g* configuration, to provide the working environment for up to three astronauts. A total of 16 racks can be carried in four segments of four racks each.

The central area of the starboard cone is

Fig. 3. Mock-up of the Columbus interior.

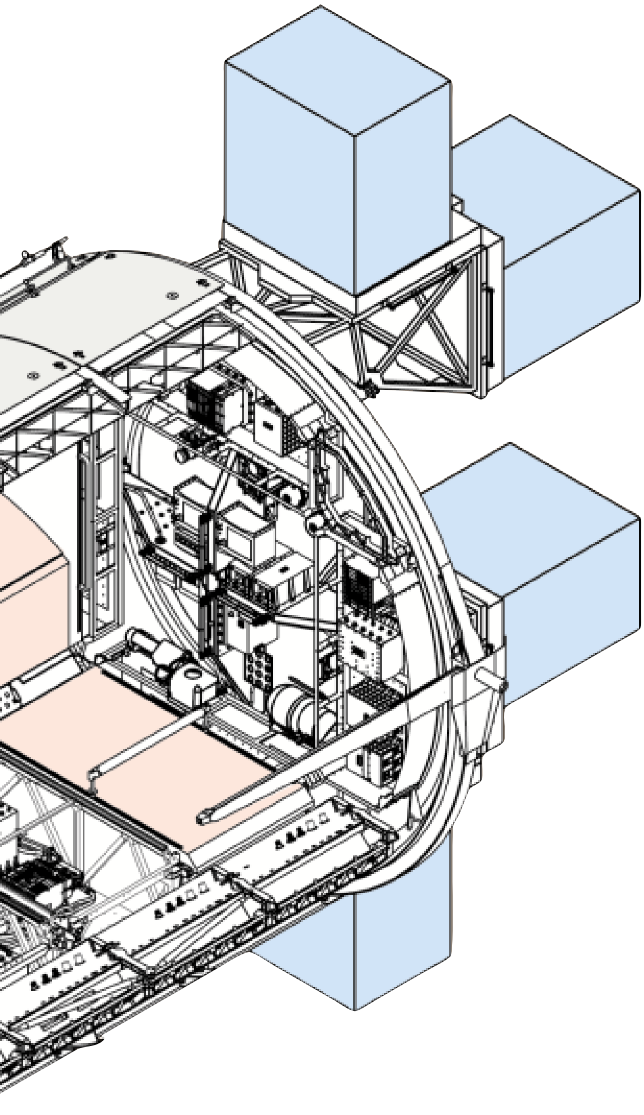


Fig. 4. Cutaway view of Columbus.

configured for system equipment that requires undisturbed crew viewing and handling access, such as video monitors and cameras, switching panels, audio terminals and fire extinguishers. The remainder of the system equipment is housed in the rest of the endcone areas and three of the deck (floor) racks. That leaves 13 racks available for payloads, of which 10 are fully outfitted with resources for payloads (each can house 700 kg on-orbit in 1.5 m^3) and three provide passive stowage accommodation.

The cabin is ventilated by a continuous airflow entering via adjustable air diffusers on the upper stand-offs, sucked in from the Station by a fan centred below the hatch in the port cone. The internal layout is shown in Figs.3-6.

Each active payload rack location is compatible with ISPR requirements. Externally, four payload support structures provide the same mechanical and functional interfaces as NASA's standardised Express Pallets for external payloads on the ISS Truss.

Functional Architecture

As with any spacecraft, the functional architecture of Columbus is complicated. Although Columbus is not autonomous – so, for example, it has no power generation or attitude control systems – it is a manned laboratory and therefore has an Environmental Control and Life Support Subsystem (ECLSS) as well as man-machine interface provisions. The overall architecture is shown in Fig. 7, together with the principal interfaces to the rest of the Station and to the payloads.

The various systems and functionality of the module are detailed in the following:

Fig. 8: the Emergency, Warning & Caution (EW&C) block diagram shows that all safety-related parameters – whether of the system or of the payloads – are monitored and brought together on a dedicated redundant set of computers (the Vital Telemetry Computers, VTCs), which alerts the Station in the event of a problem aboard Columbus. 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 & Control (C&C) bus.

Fig. 9: the end-to-end communications infrastructure is such that all data collected aboard Columbus – be they system housekeeping, low- or high-rate payload data, or video data – are multiplexed and then passed through the Station to either the NASA Tracking & Data Relay Satellite System (TDRSS) or the Japanese/ESA Data Relay & Test Satellite (DRTS)/Artemis systems and thence to the control centres, for onward transmission to the users. (Uplink command data from the ground is via only TDRSS.)

Fig. 10: shows the corresponding Columbus onboard block diagram for communications.

Fig. 11: Station power is generated centrally by huge solar wings. This 120 Vdc system routes power to all Station users. Inside Columbus, the power goes through the central Power Distribution Unit (PDU) and from there, as 120 Vdc or 28 Vdc, to all payload racks, external platform locations, centre aisle standard utility panels and subsystems.

Fig. 12: the internal Columbus Data Management System (DMS) is shown. General data are separated from safety-related data as explained above. MIL bus and Ethernet local area network media are accessible to all payload locations, and a series of computers services all user needs. Crew interfacing is available via laptops, which can be plugged into the system at any location.

Fig. 13: in a similar manner to the DMS, the software architecture is segregated such that safety-related packages, system monitoring and payload packages are defined and distributed to serve the end users most efficiently. This figure shows the types of services and their locations on the various computers.

Fig. 14: Columbus active thermal control is via a water loop serving all payload rack locations. It is connected to the ISS centralised heat rejection system via interloop heat exchangers. In addition, there is an air/water heat exchanger to remove condensation from the cabin air.

Fig. 15: the module is wrapped in goldised Kapton Multi Layer Insulation to minimise overall heat leaks. A system of electrical heaters combats the extreme cold possible at some Station attitudes. These heaters will be activated during both the launch and the transfer from the Shuttle cargo bay to Node-2, drawing on the SSRMS power supply.

Fig. 16: as with many other ISS systems, the life support system is centralised. Columbus air circulation is driven by fans taking fresh air from Node-2, passing the air through diffusers into the cabin for crew ventilation, and then back to the Node for freshening and carbon dioxide removal. The crew can control temperature and humidity, and air content is monitored for contamination from the systems or payloads. Pressure control and relief are also available.

The systems resources briefly described above are distributed to the payloads via standard connections. Fig. 17 (payload racks), Fig. 18 (centre aisle) and Fig. 19 (EPF) show these connections. In addition, a venting and vacuum capability is provided at each of the 10 active ISPR locations for the payloads, as shown in Fig. 20.

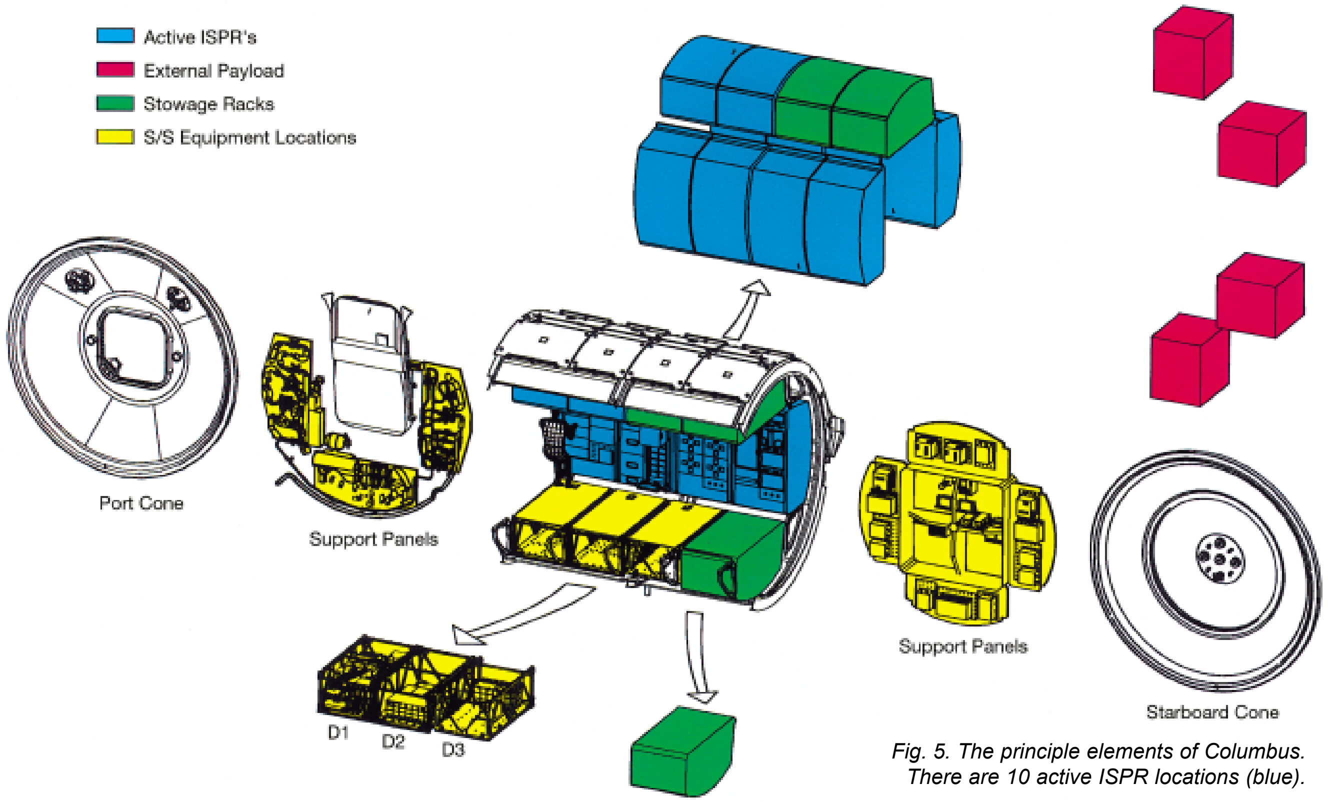


Fig. 5. The principle elements of Columbus. There are 10 active ISPR locations (blue).

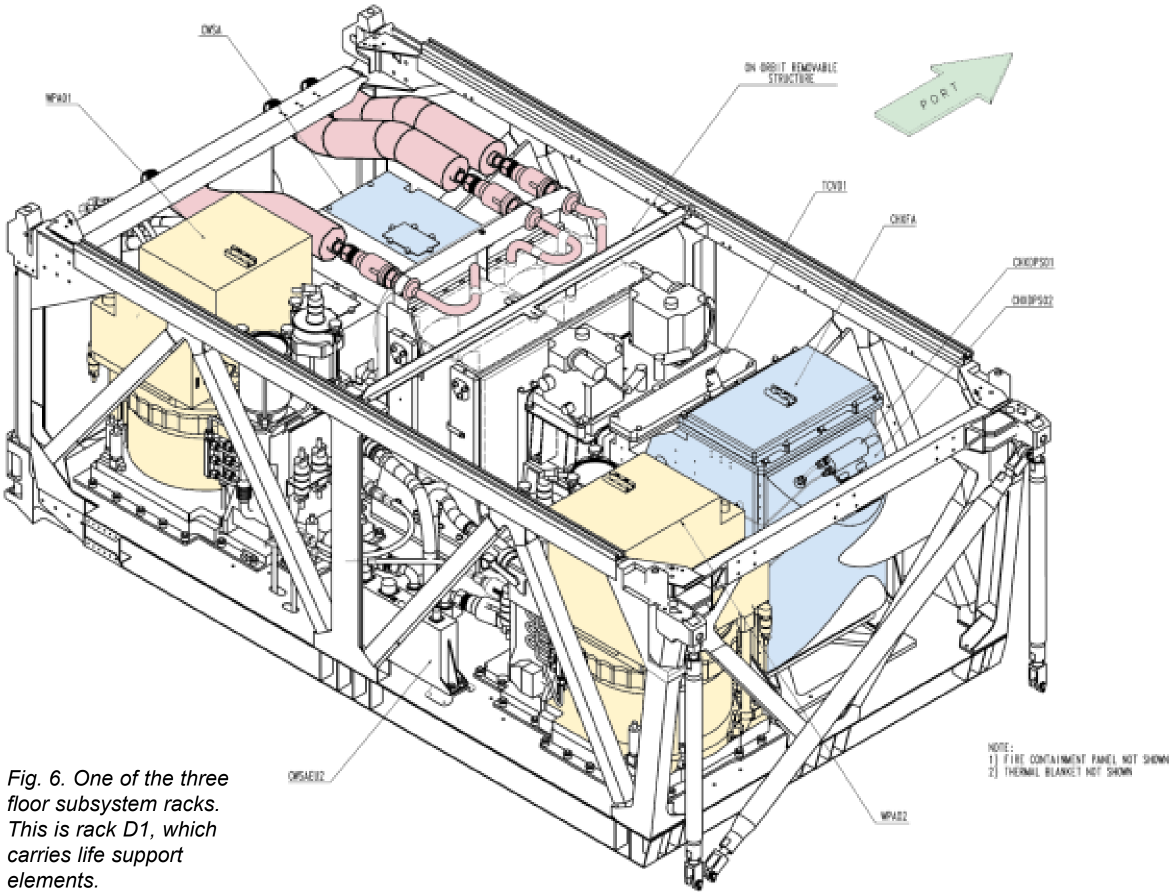


Fig. 6. One of the three floor subsystem racks. This is rack D1, which carries life support elements.

Fig. 7. Columbus system functional architecture.

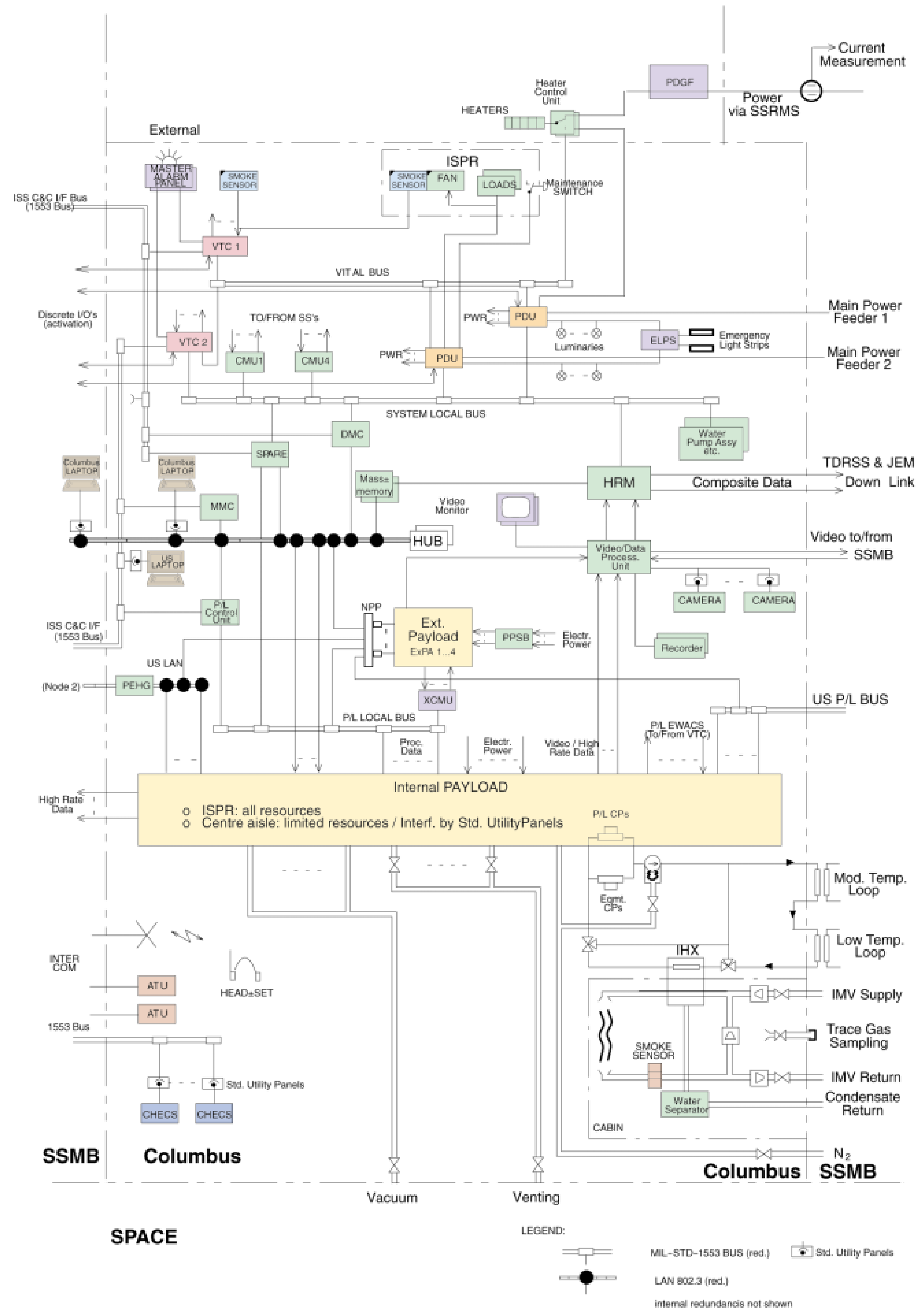


Fig. 8. Emergency, Warning and Caution: all safety-related parameters are brought together on the VTCs.

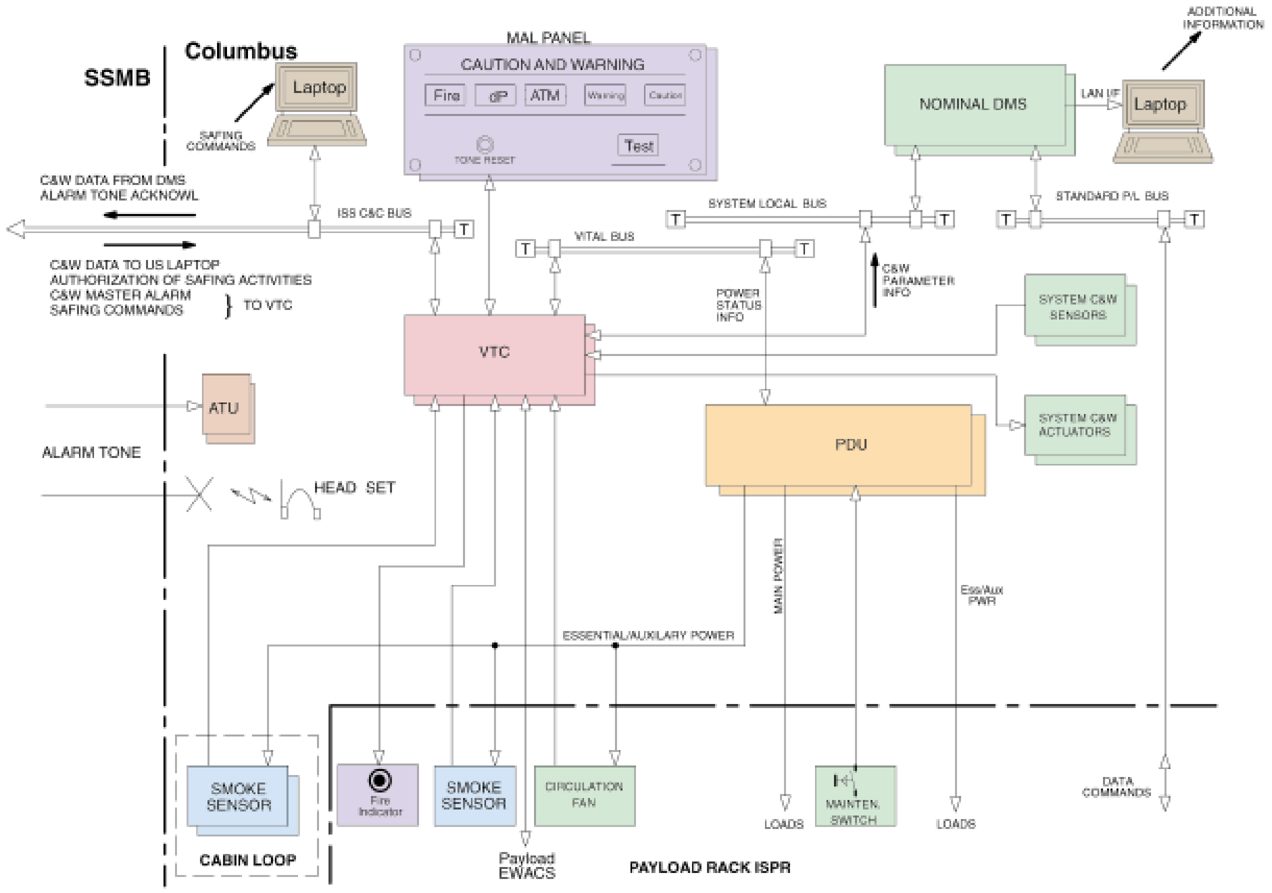
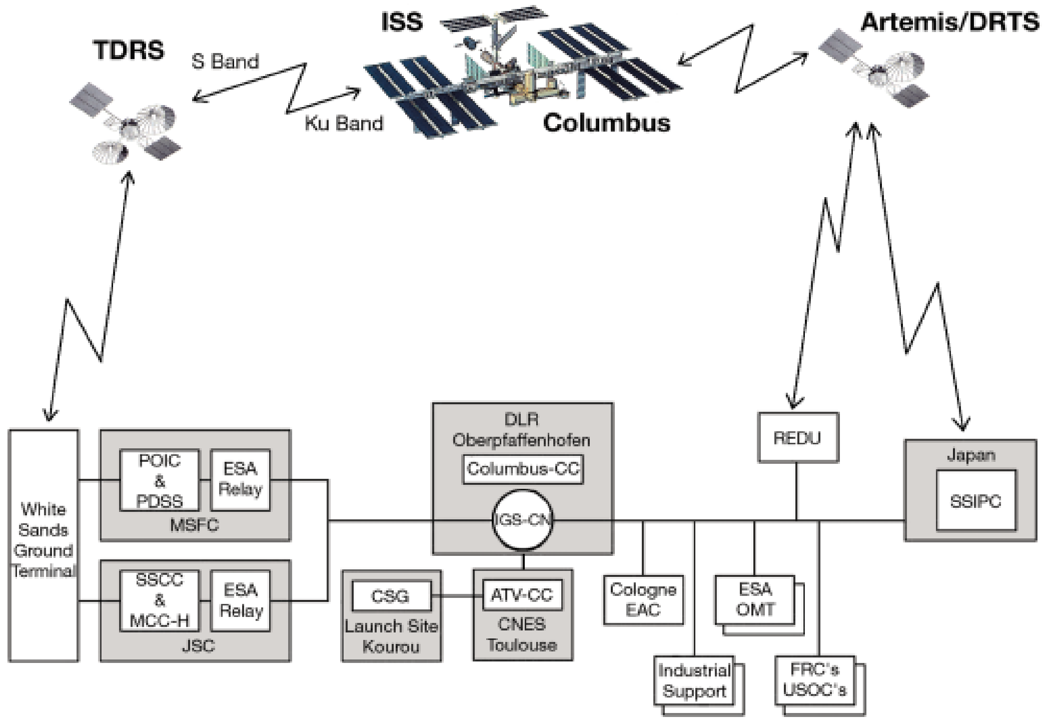


Fig. 9. The end-to-end communications infrastructure for Columbus. (ESA)



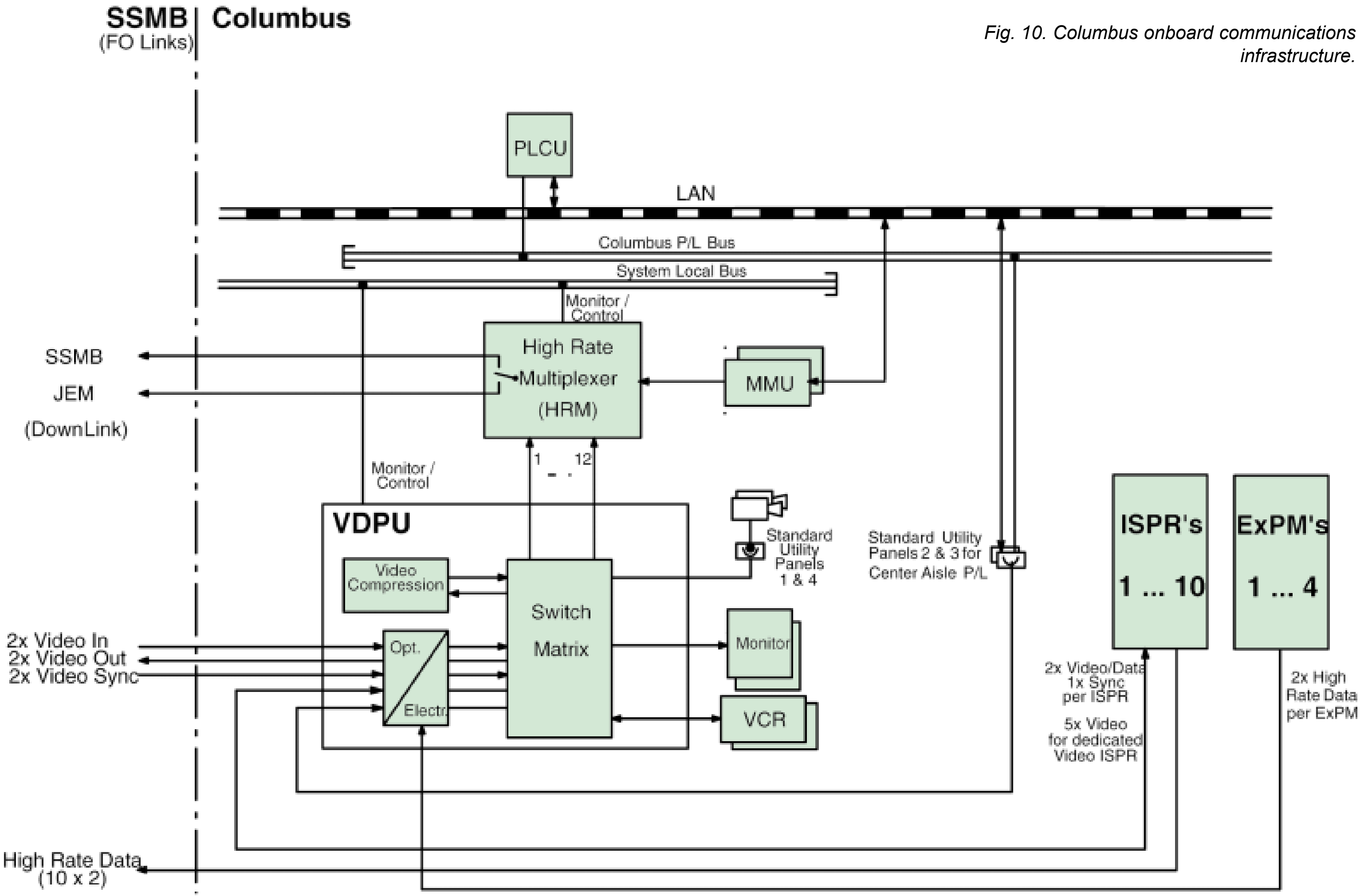
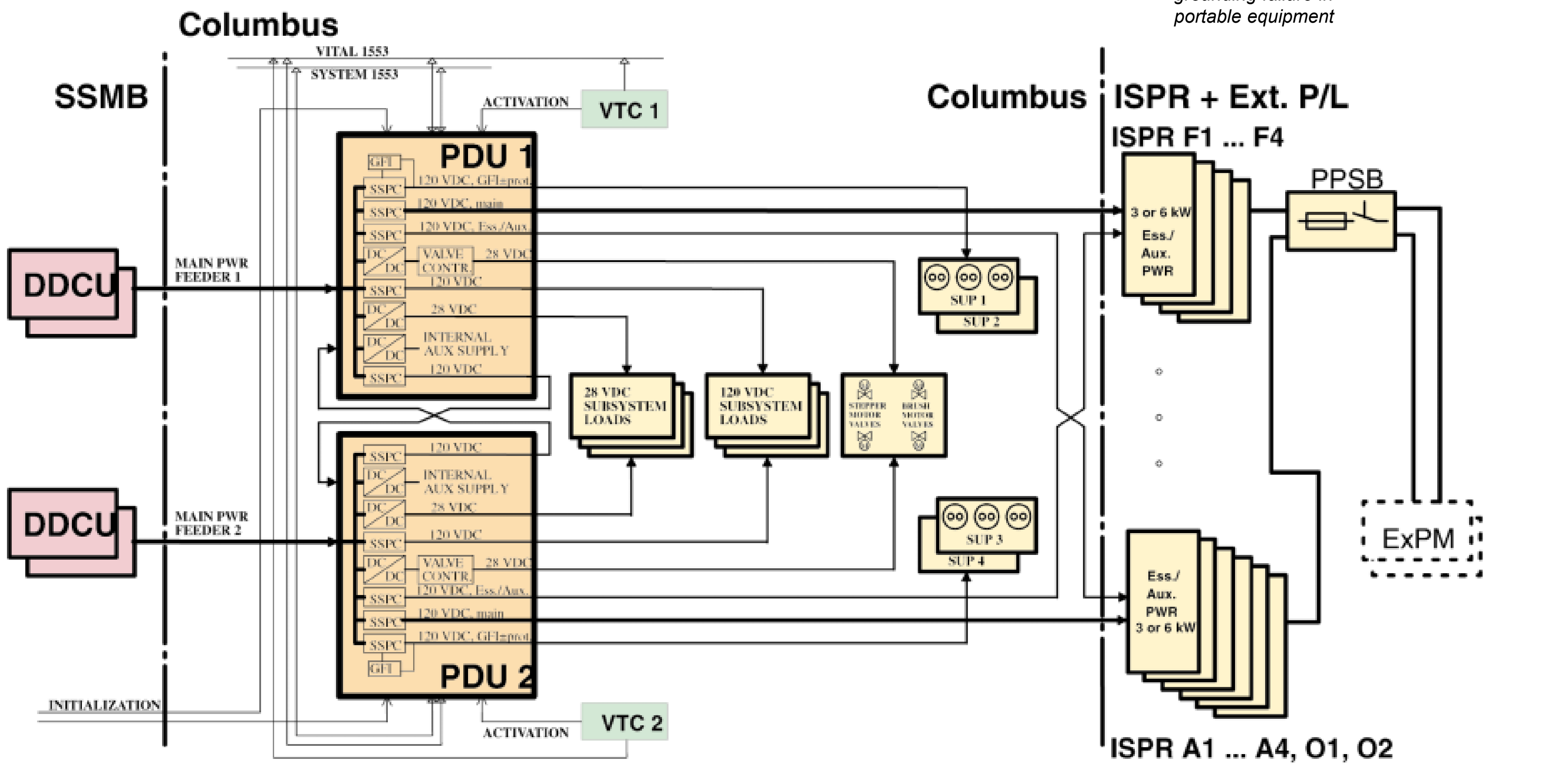


Fig. 10. Columbus onboard communications infrastructure.

Fig. 11. Columbus power distribution.

- *designed for up to 18 kW total power to subsystems and payload, maximum 13.5 kW to payload*
- *120 Vdc and 28 Vdc supply for Columbus equipment; 120 Vdc supply for payload*
- *all 120 Vdc outputs protected/switched by Solid-State Power Controllers (SSPCs)*
- *Standard Utility Panel power outlets protected with Ground Fault Interruptor (GFI) to ensure ground safety even with grounding failure in portable equipment*
- *2x1.25 kW available per ExPM location, total 2.5 kW external payload power*



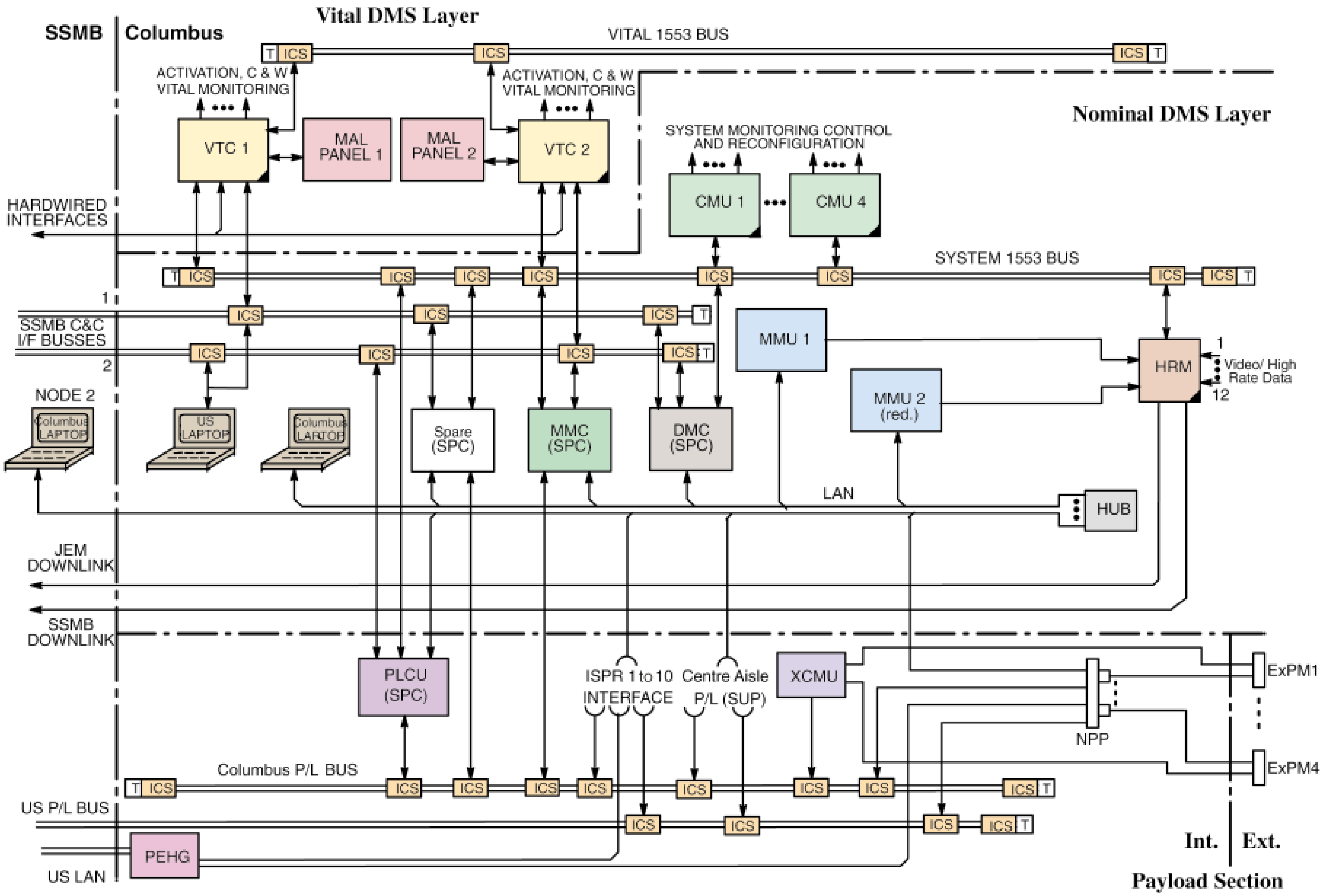


Fig. 12. The Columbus Data Management System.

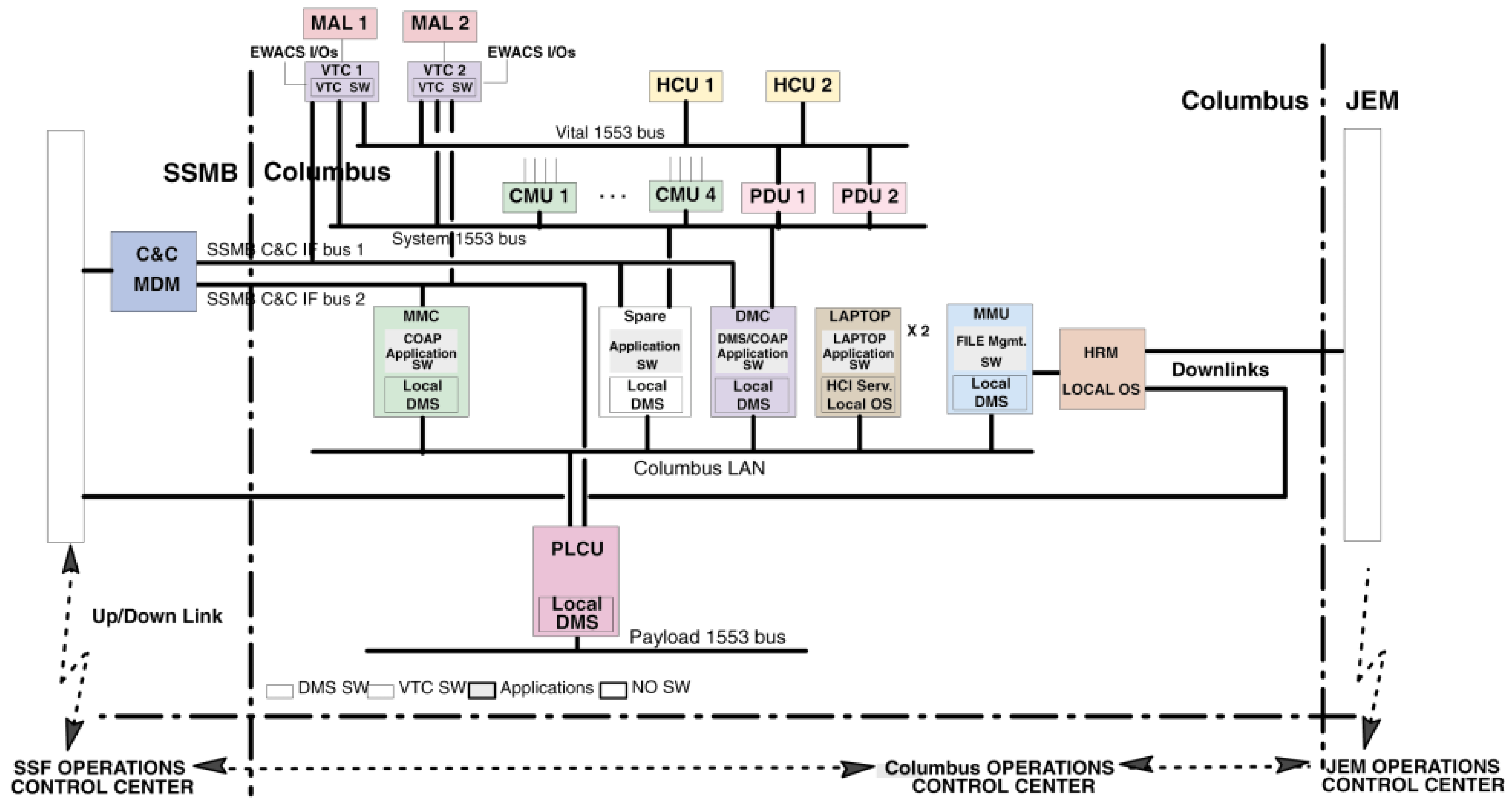


Fig. 13. The software architecture for Columbus.

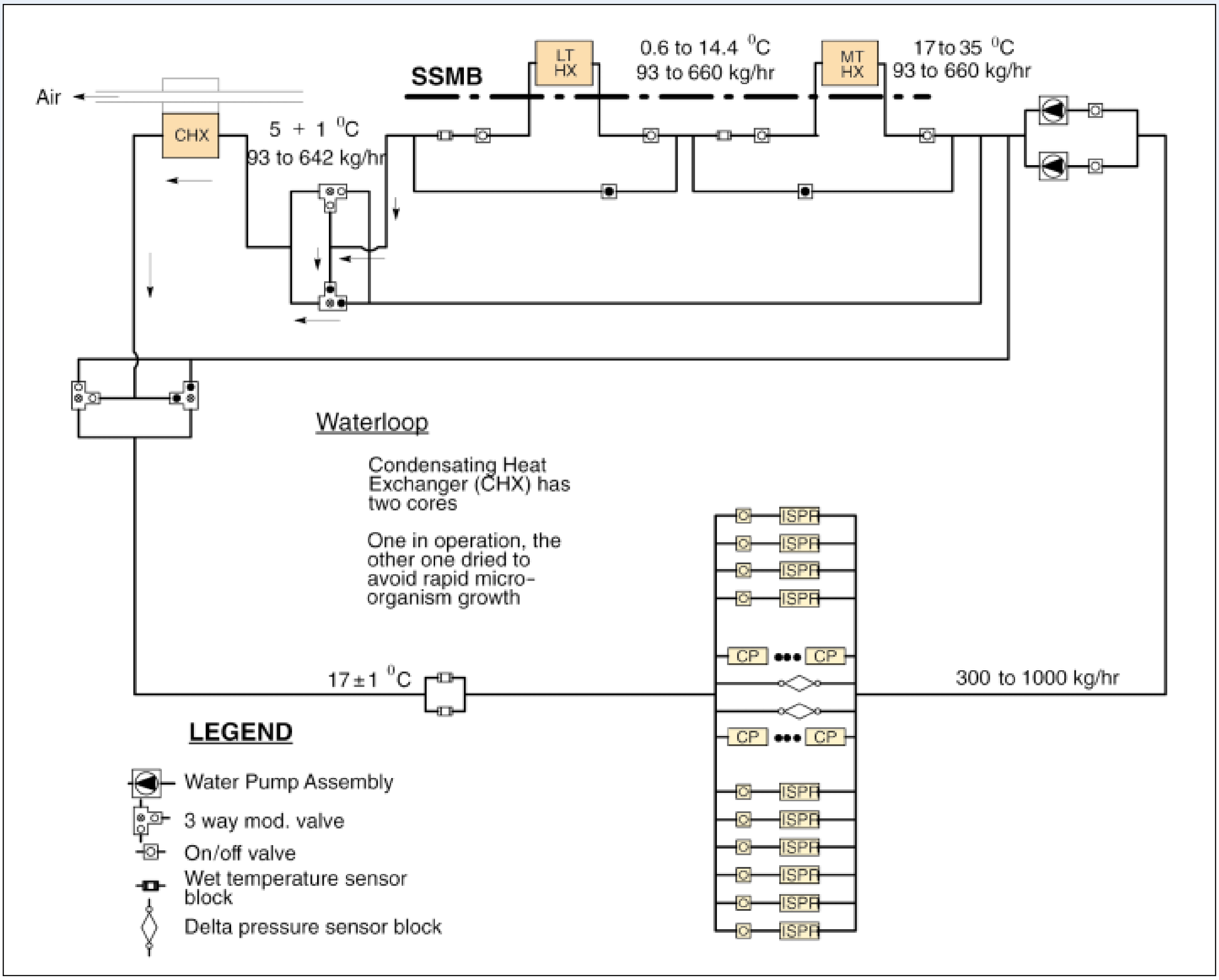
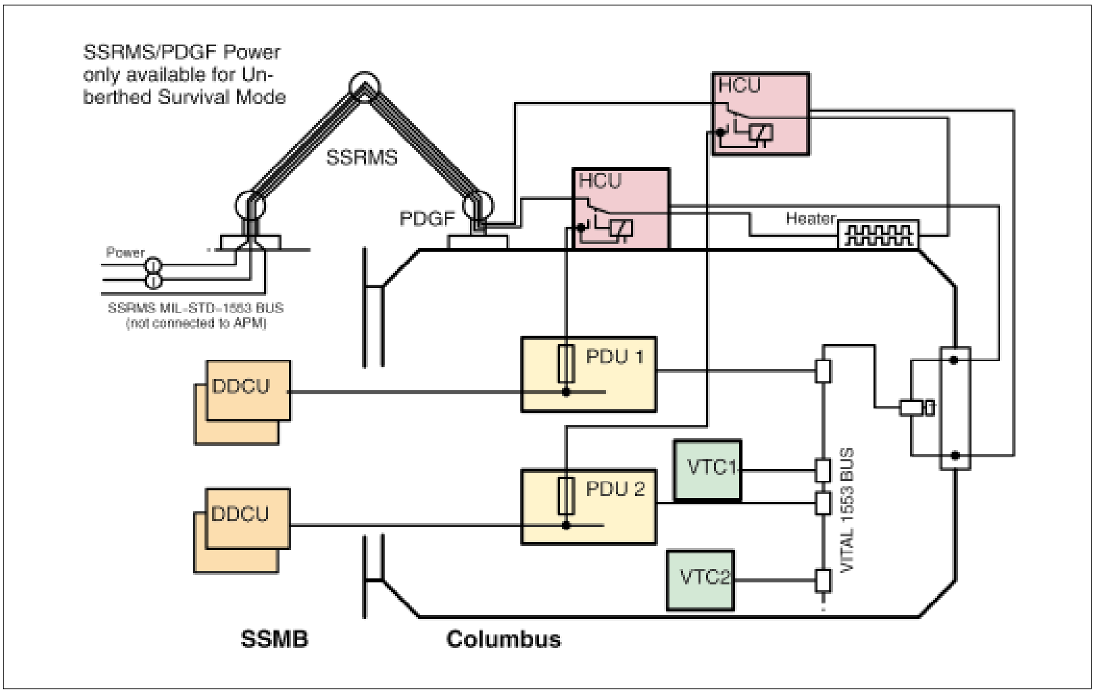


Fig. 14. The Columbus active thermal control system.

Fig. 15. Columbus passive thermal control and heaters.



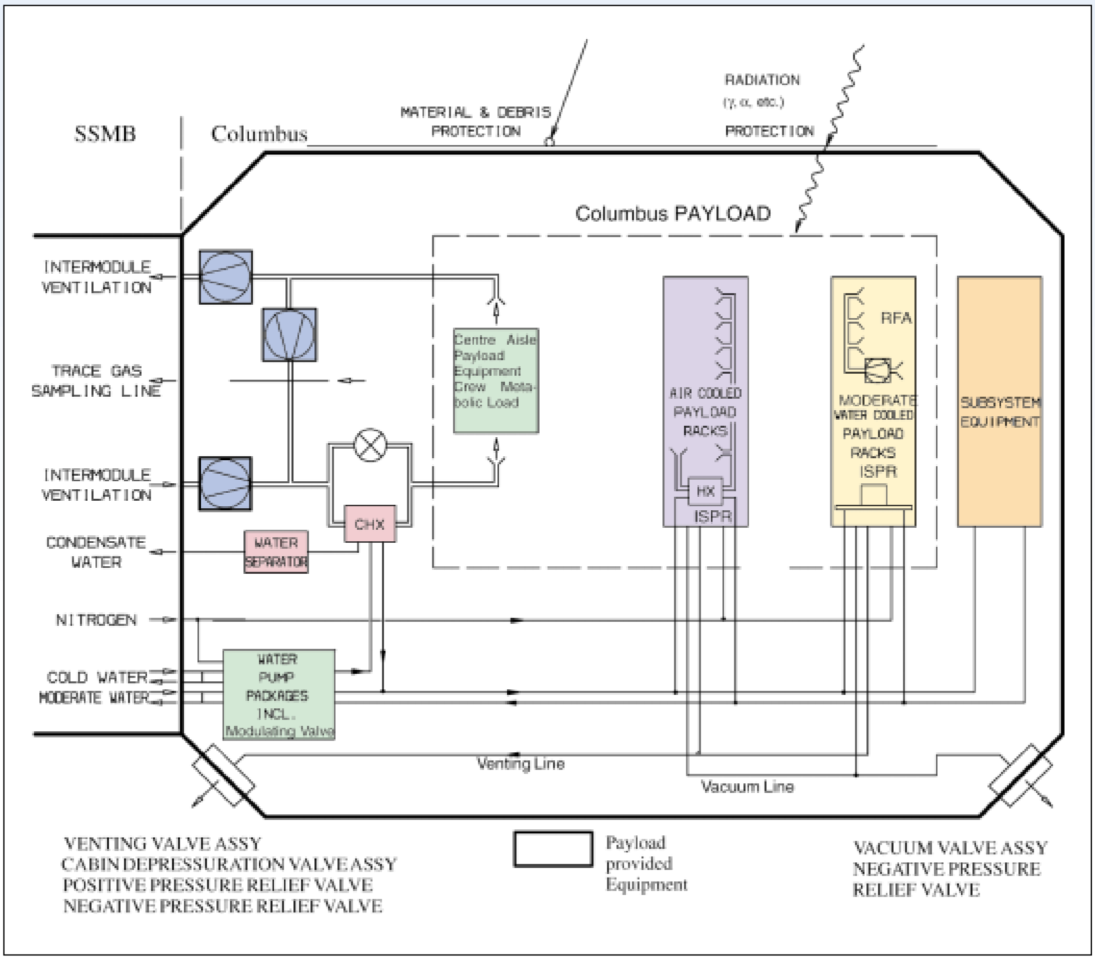
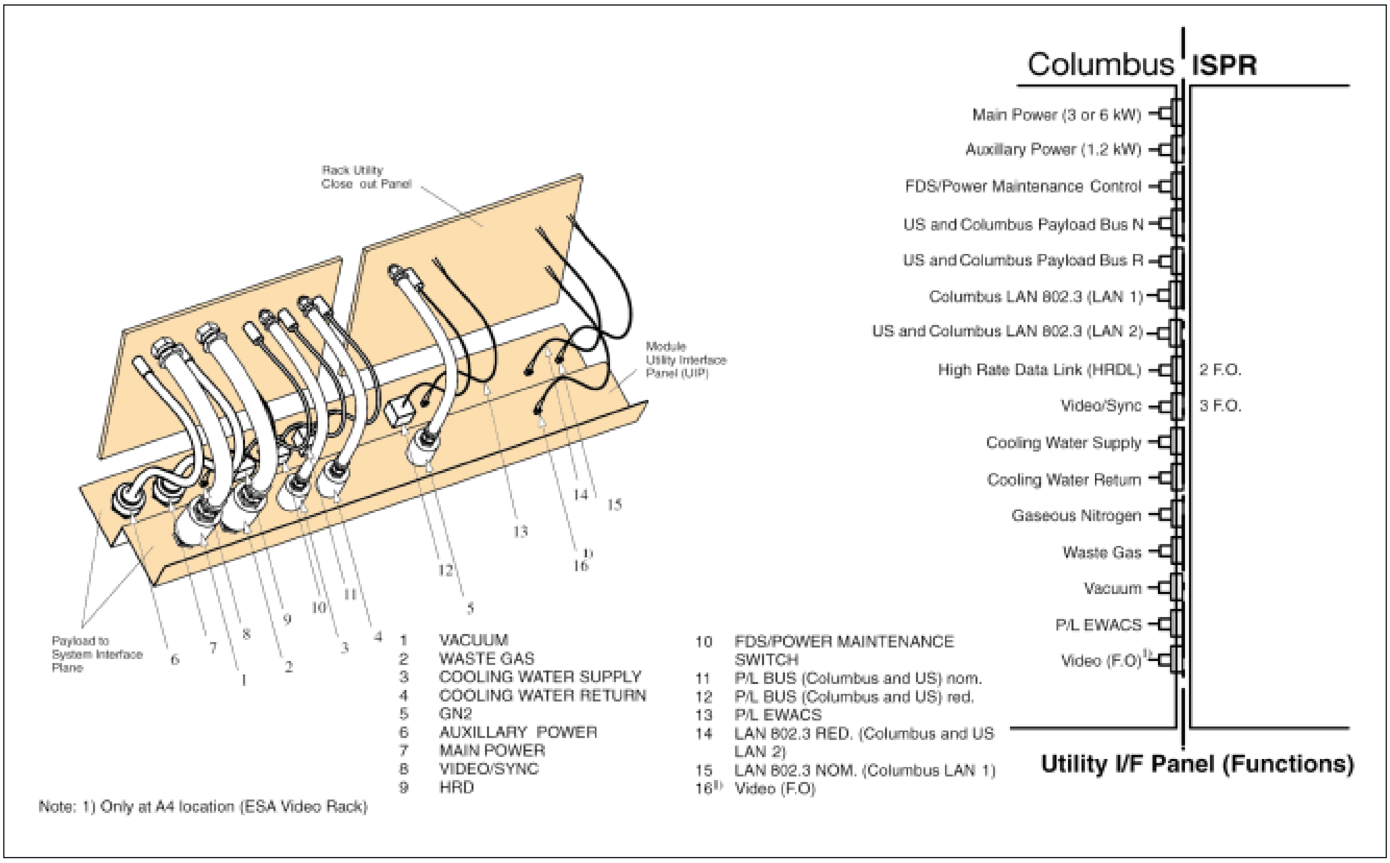
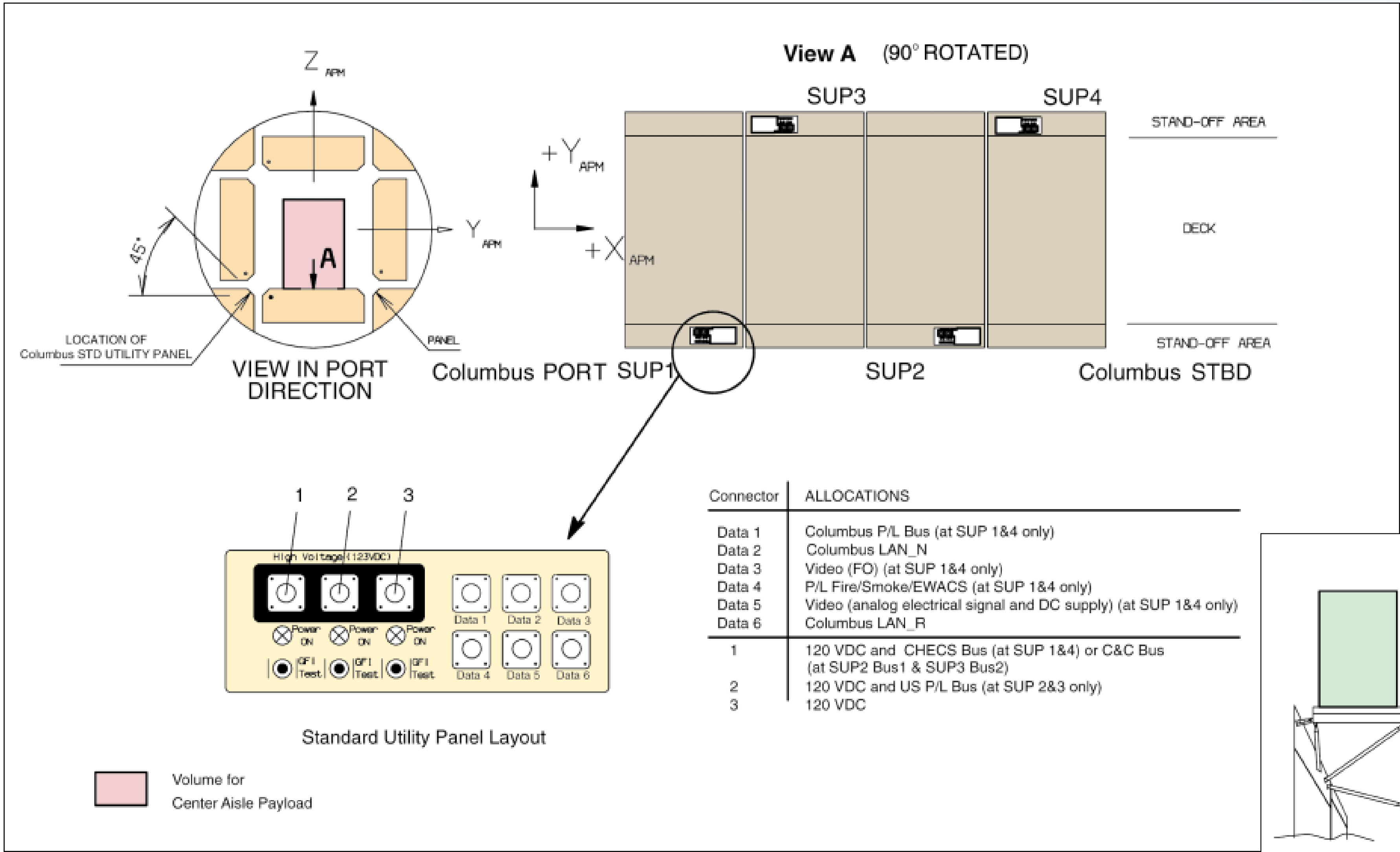


Fig. 16. The Columbus environmental control system.

Fig. 17. System resources available via the ISPR Utility Interface Panel.





Connector	ALLOCATIONS
Data 1	Columbus P/L Bus (at SUP 1&4 only)
Data 2	Columbus LAN_N
Data 3	Video (FO) (at SUP 1&4 only)
Data 4	P/L Fire/Smoke/EWACS (at SUP 1&4 only)
Data 5	Video (analog electrical signal and DC supply) (at SUP 1&4 only)
Data 6	Columbus LAN_R
1	120 VDC and CHECS Bus (at SUP 1&4) or C&C Bus (at SUP2 Bus1 & SUP3 Bus2)
2	120 VDC and US P/L Bus (at SUP 2&3 only)
3	120 VDC

Fig. 18. Resources available to payloads in the centre aisle.

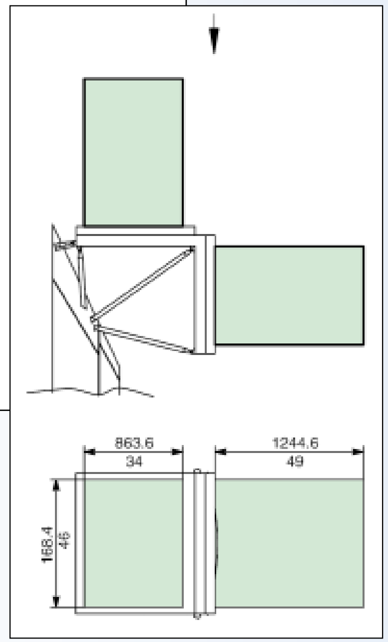


Fig. 19. Resources available to payloads on the External Payload Facility. Functional interfaces: power 120 Vdc, 1.25 kW per Feeder, 2.5 kW total; 32 MBytes/s; data management Columbus payload bus + LAN, alternative US payload bus + US LAN.

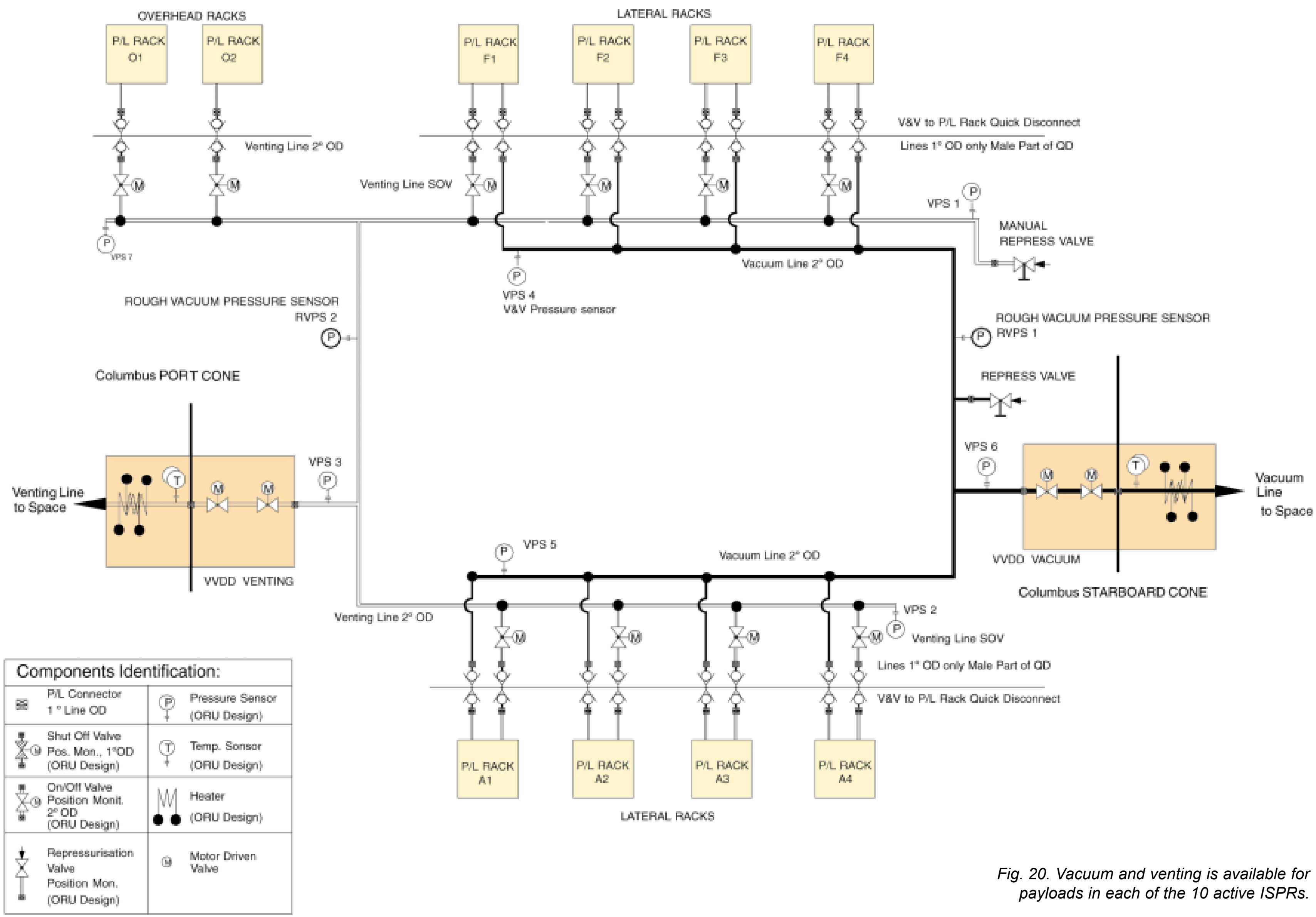


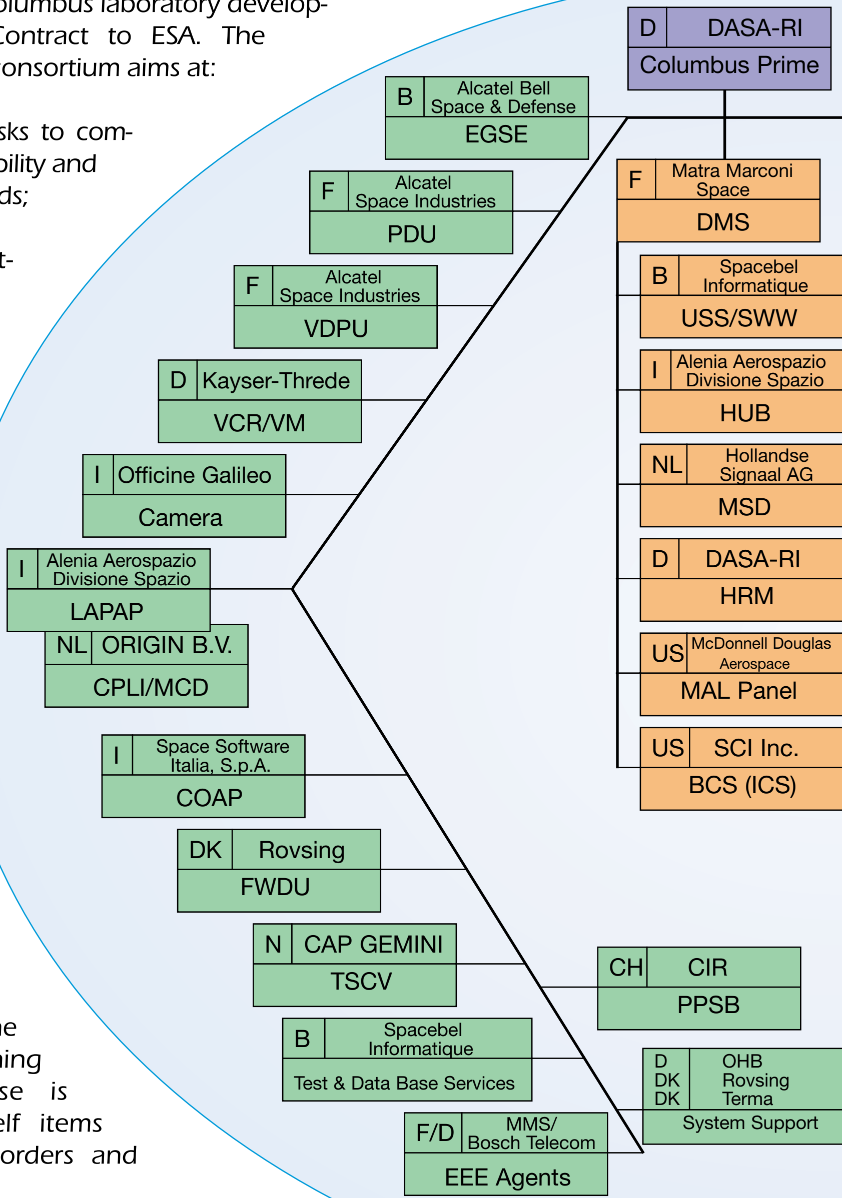
Fig. 20. Vacuum and venting is available for payloads in each of the 10 active ISPRs.

Industrial Consortium

An industrial consortium led by DaimlerChrysler Aerospace AG (DASA) is undertaking the Columbus laboratory development under a Fixed Price Contract to ESA. The distribution of work within the consortium aims at:

- allocating the appropriate tasks to companies with the greatest capability and experience in the relevant fields;

- achieving the most cost-effective development, taking into account the stringent ceiling price target set by the Agency. To this end, maximum use is being made of common European and ISS items. Common European developments include the primary structure and life support items from the Multi-Purpose Logistics Module (based on an ESA/ASI inter-agency arrangement), and Data Management System items from the Russian Service Module (the ESA DMS-R contract). Common ISS items include the hatch and Common Berthing Mechanism. Maximum use is being made of off-the-shelf items such as video cameras/recorders and laptop computers;



- minimising expenditure outside of participating states, so long as equivalent items could be developed in Europe at a comparable price;

- using equipment-level competition as a mechanism to achieve low prices.

The resulting industrial consortium is shown in Fig. 21. The organigramme has the following specific aspects:

- a very important role is allocated to Alenia Aerospazio. Building on the reuse of significant MPLM elements (structure, thermal control and ECLS equipment), Alenia Aerospazio is responsible for the overall physical configuration, thermo-mechanical system design and Columbus pre-integration.

- only two classical subsystem contracts have been placed: the Data Management System with Matra Marconi Space and the Environmental Control and Life Support Subsystem with Dornier. All other units are subcontracted at the equipment/assembly level, thus eliminating a management layer in part of the programme.

The selected companies represent some of the most skilled and experienced European aerospace contractors, many of them with manned space experience through the Spacelab and Eureca projects.

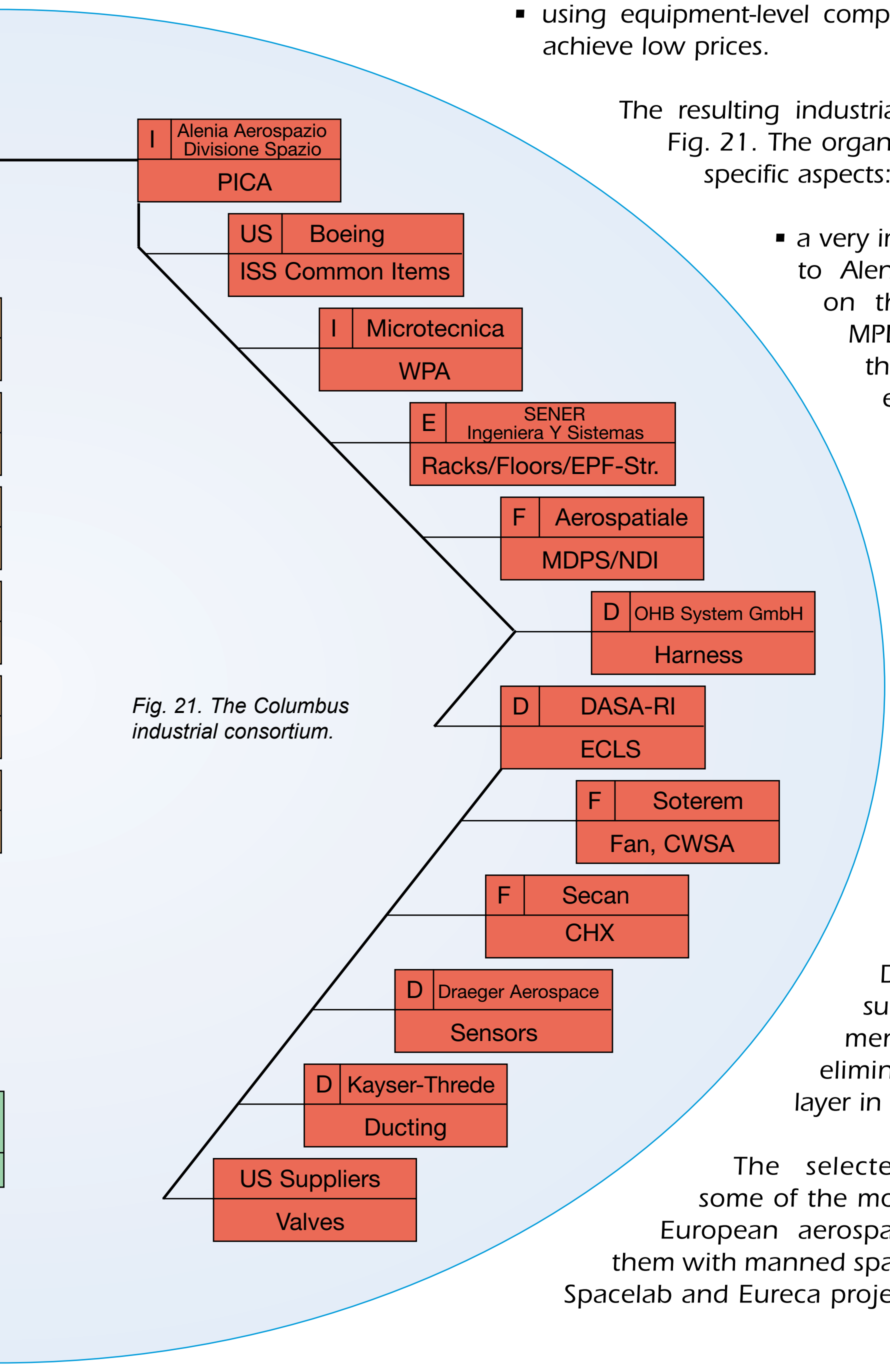


Fig. 21. The Columbus industrial consortium.

Columbus Development

Overall Principles

Columbus development revolves around the classical project review system of Preliminary Design Review (PDR), Critical Design Review (CDR), Qualification Review (QR) and Acceptance. Such reviews are conducted at the prime contractor/systems level by ESA, and are based on corresponding lower level reviews conducted by the prime and lower level contractors. Phase C/D began in January 1996. The launch date is a function of the overall ISS assembly schedule, which has suffered significant delays in its early stages, but the availability of the Columbus flight unit is not on a critical path. However, because the module will be launched with some 2500 kg of payloads, their development must be harmonised so that, before final acceptance, they are integrated into the laboratory and checked out to ensure compatible interfaces.

The System PDR was successfully concluded in late 1997, and the CDR is foreseen for mid-2000. Launch is expected to be early 2004.

'Model' Philosophy and Commonality

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 are being adopted (Fig. 22 and Table 2) without further qualification, after proof that their original requirements meet or exceed those of Columbus.

In order to minimise programme costs, commercial video equipment is being adapted by adding interface circuitry and housings for Columbus. Their qualification is within the off-the-shelf philosophy, which requires more stringent environmental criteria to compensate for the uncertainties of the reduced design and manufacturing transparency.

The overall Columbus system functional architecture (including all onboard

Table 2. Columbus Units Sourced from Other Projects.

Source: International Space Station
Power Data Grapple Fixture (PDGF) Smoke Sensor Portable Fire Extinguisher (PFEX) Portable Breathing Apparatus (PBA) Audio Terminal Unit (with cold plate) Audio Antenna Common Berthing Mechanism (passive half) Hatch Laptop Master Alarm Panel Payload Ethernet HUB/Gateway (PEHG) Flight Release Attachment Mechanism for EPF I/F Module Lighting Unit Emergency Lighting Unit
Source: Multi-Purpose Logistics Module
Primary Structure Cabin Air Diffuser Cabin Depressurisation Assembly Line Shut-off Valve Positive/Negative Pressure Relief Assembly
Source: DMS-R
Computer items Mass Memory Unit item
Source: Off-The Shelf (OTS)
Video Monitor Video Recorder Video Camera

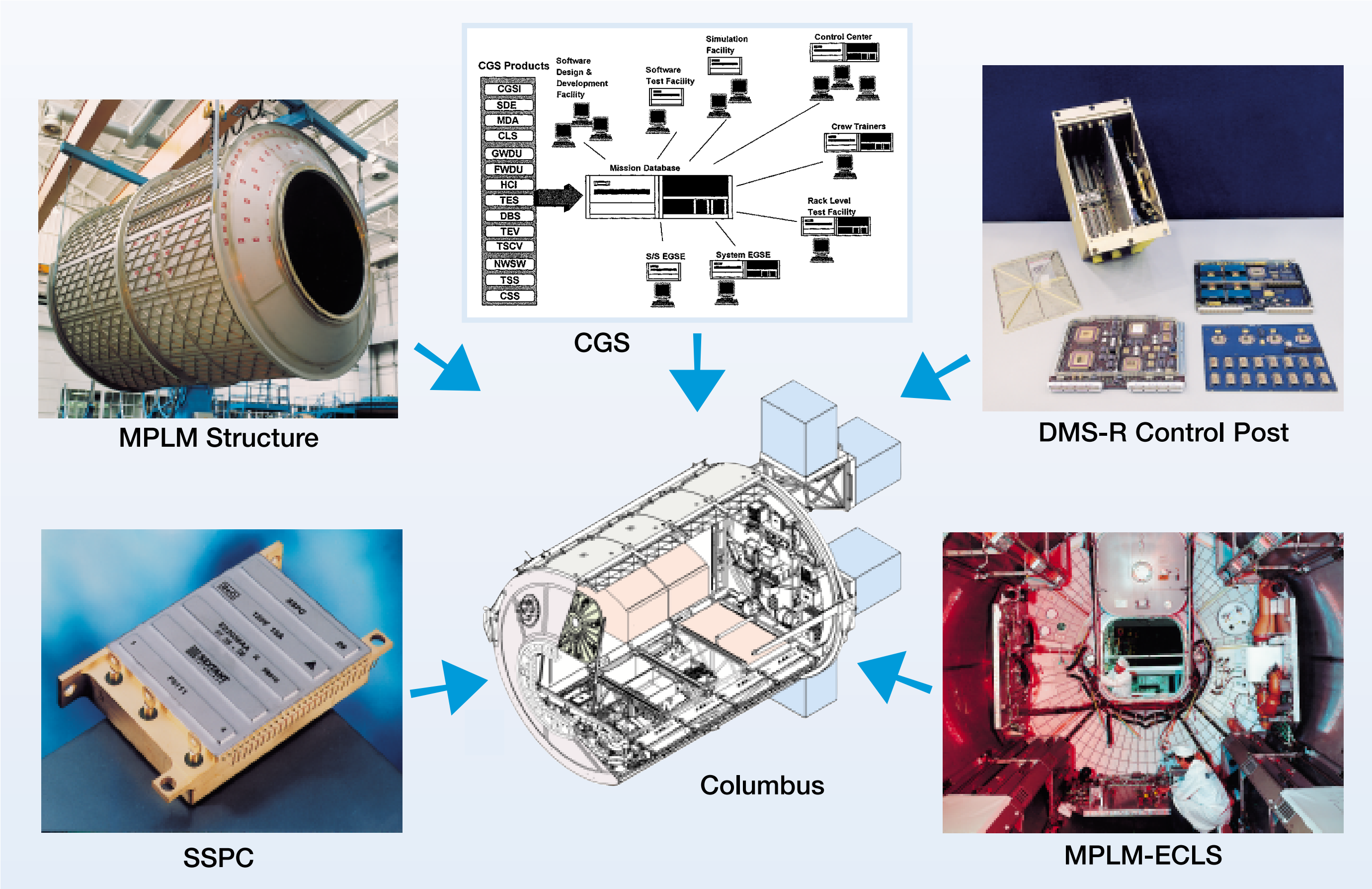


Fig. 22. Examples of elements from other projects adopted for Columbus.

software) will be proved on an Electrical Test Model (ETM) at DASA's Bremen facilities. The ETM includes the complete power distribution and data management system; all other functional onboard units will be represented by at least one Engineering Model (EM) per unit type for interface compatibility testing. The EM units will be identical to the Flight Models in physical and functional design (only differences in detailed manufacturing processes and parts quality are acceptable). The ETM will be functionally attached to Ground Support Equipment, which simulates the ISS and payload interfaces in order to ensure end-to-end testing. The ETM will not contain representative primary or secondary structures, but will have a fully representative set of power and data harnesses.

All other items of the Columbus system are simulated such that all system functions can be exercised during the ETM test campaign and, later, be used for trouble-shooting in parallel to the Flight Model assembly, integration and test phase.

After ETM testing has been completed, the model will be extended to become the Rack Level Test Facility (RLTF) by adding flight-identical mechanical and thermal interfaces to support payload interface verification. The payloads will thus be tested in a high-fidelity Columbus simulator. For those payloads that will be launched within Columbus, this testing will be done before their integration into the Columbus flight configuration. This will validate the RLTF's fidelity so that payloads to be added after Columbus has headed into orbit can be verified on the simulator with high confidence.

All remaining functional qualification activities that rely on an identical system configuration but which cannot be provided by the ETM (e.g. electromagnetic susceptibility, internal noise, microgravity disturbance and overall contamination levels) will be carried out on the Columbus Protoflight Model (PFM). Before the functional units are integrated within it, the Columbus flight model mechanical configuration will be subjected to dynamic modal survey tests to verify the launch and on-orbit mathematical models. Cabin ventilation was verified in February 1999 on a mock-up of the Columbus interior at

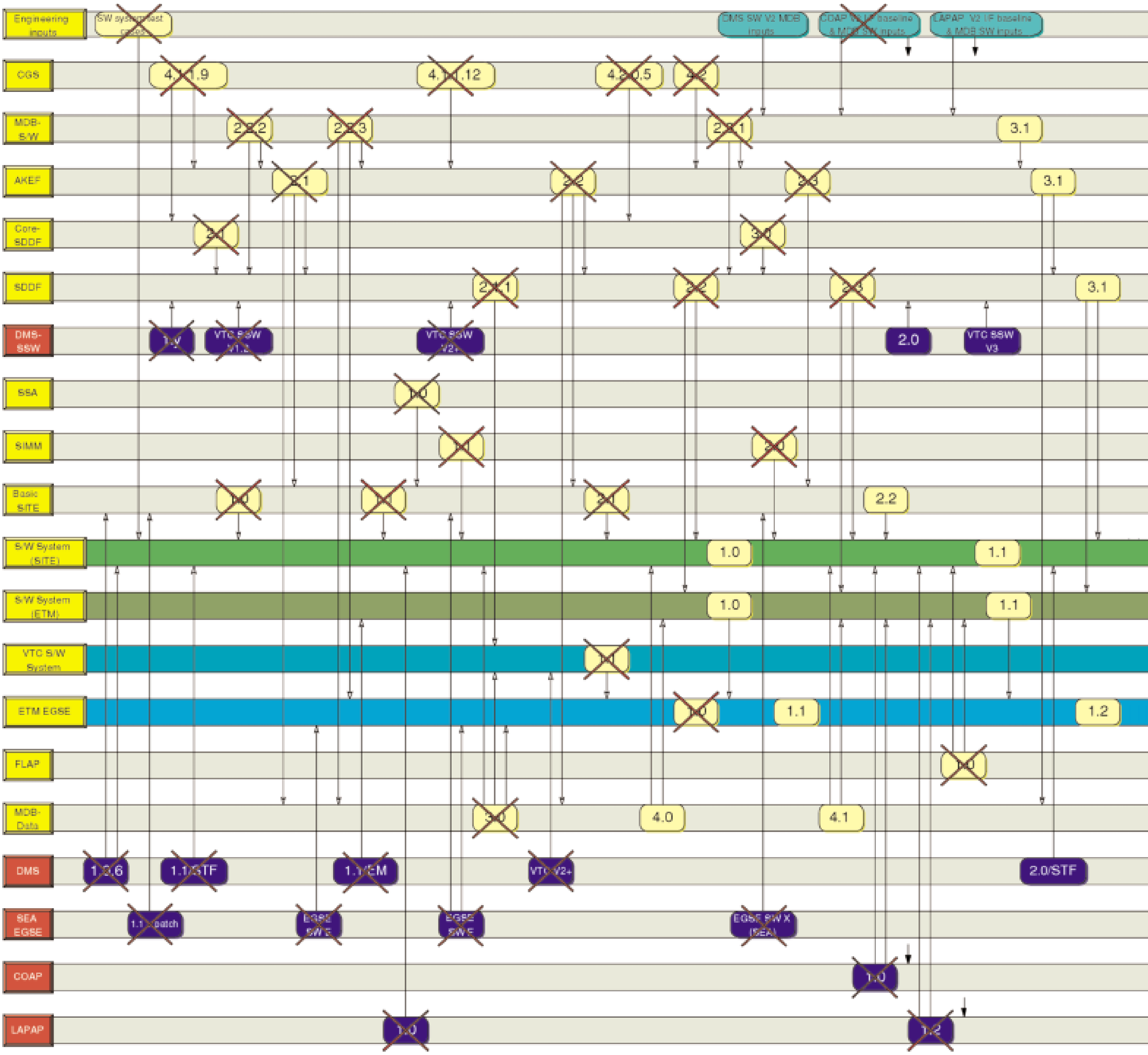


Fig. 23. Columbus system and software inter-relationships.

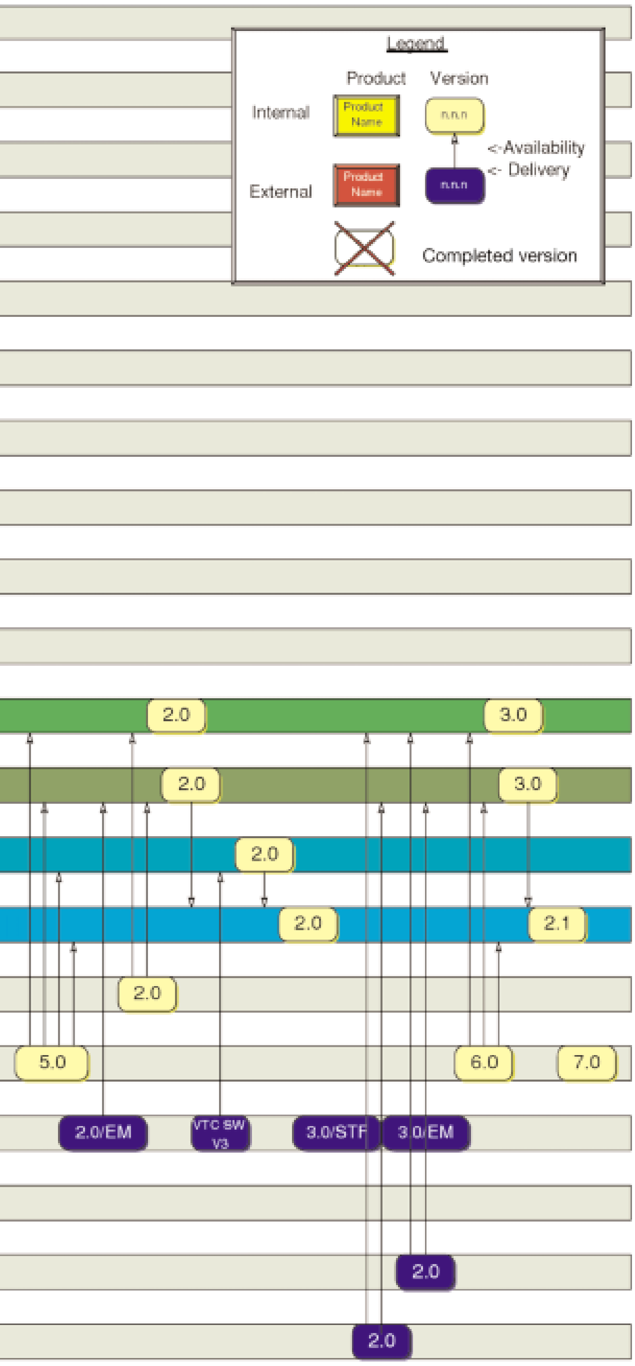
Dornier, using the fans and ducting hardware, and fire suppression demonstrations began in March 1999 on mechanical mock-ups of the relevant areas.

A mechanical mock-up is used at Alenia in Turin to demonstrate and qualify on-orbit maintenance procedures – replacement of functional units and local repairs to, for example, the structure and harness. The test campaign at 1 *g* has been completed, as has the first 'zero-gravity' verification, which was performed in a water tank at Alenia. This simulated internal operations and was performed with ESA and NASA astronauts. Final zero gravity verification of external operations will be done at NASA Johnson.

The mock-up and ETM/RLTF will both support operational evaluation and troubleshooting analyses during the entire life of the Columbus laboratory.

Software Development

The Columbus programme involves a large number of different software items



(onboard and in GSE) that are being developed, integrated and used concurrently by several contractors. This means that common standards must be enforced for design, documentation, review and release procedures and detailed software module interface definitions. Therefore a standardised set of development tools and facilities has been imposed. Equally, it is necessary to maintain adequate margins for computer performances and memory sizes, which are progressively released only at defined events ('margin management').

All flight software developed by subcontractors will be delivered for integration with the flight application and DMS software, and for testing on the Software Integration and Test Environment (SITE) before use on the ETM. The final qualification of flight software will be performed as part of the overall end-to-end functional Columbus qualification.

Several thousand housekeeping data end items have to be acquired and processed by software in order to minimise crew and ground involvement in operation of the complex Columbus system, in addition to supporting failure detection and isolation during maintenance. All of this information is collected in a ground-based Mission Data Base, which is also the foundation for the later utilisation of Columbus when setting up the complete onboard software, including the payload and its related ground station operational procedures.

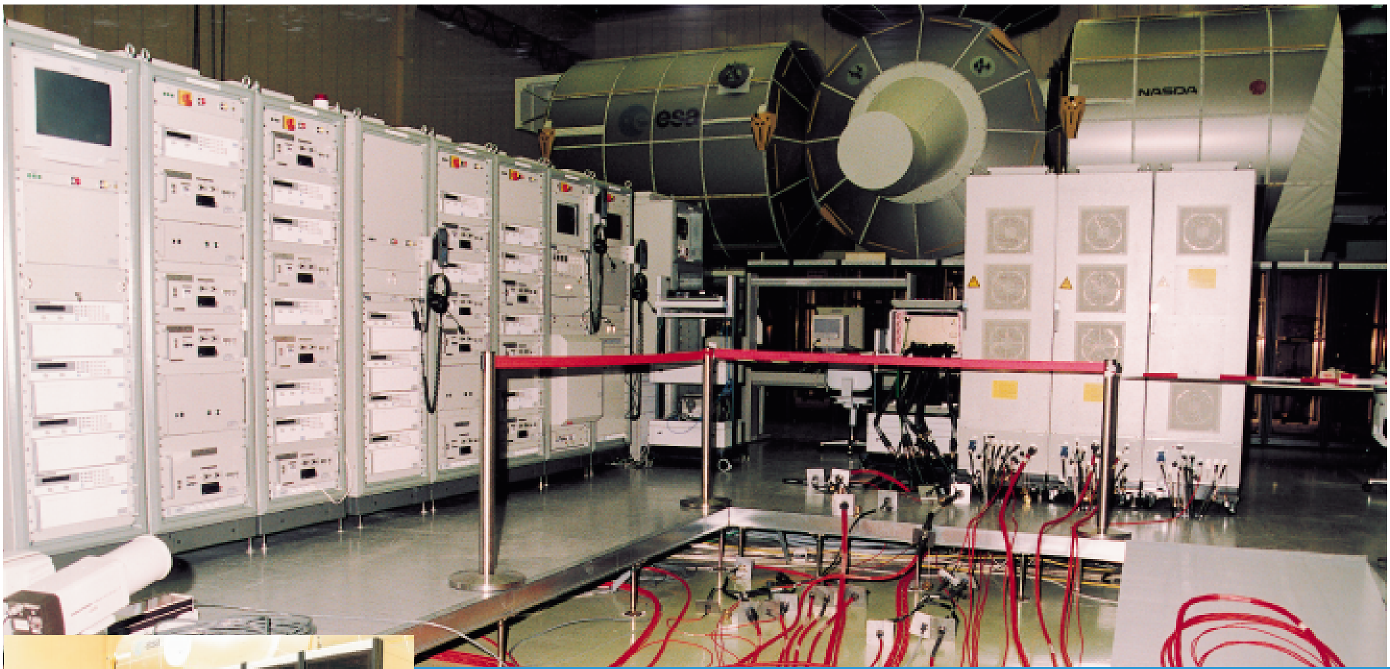
There is special emphasis on software involved in critical functions. In general, the involvement of software in safety-critical functions is minimised.

The end product is a highly complicated set of software with many interfaces and functions. A measure of the complexity can be seen in Fig. 23, which shows the elements of the software packages and how they will be integrated into the overall system package.

Development Status

System Level
Following the successful Columbus PDR in December 1997, the system design has been established, as scheduled in the Columbus Design and Development Plan. A number of significant safety-related modifications arising from the PDR have been implemented:

- modification of the configuration to improve fire suppression;



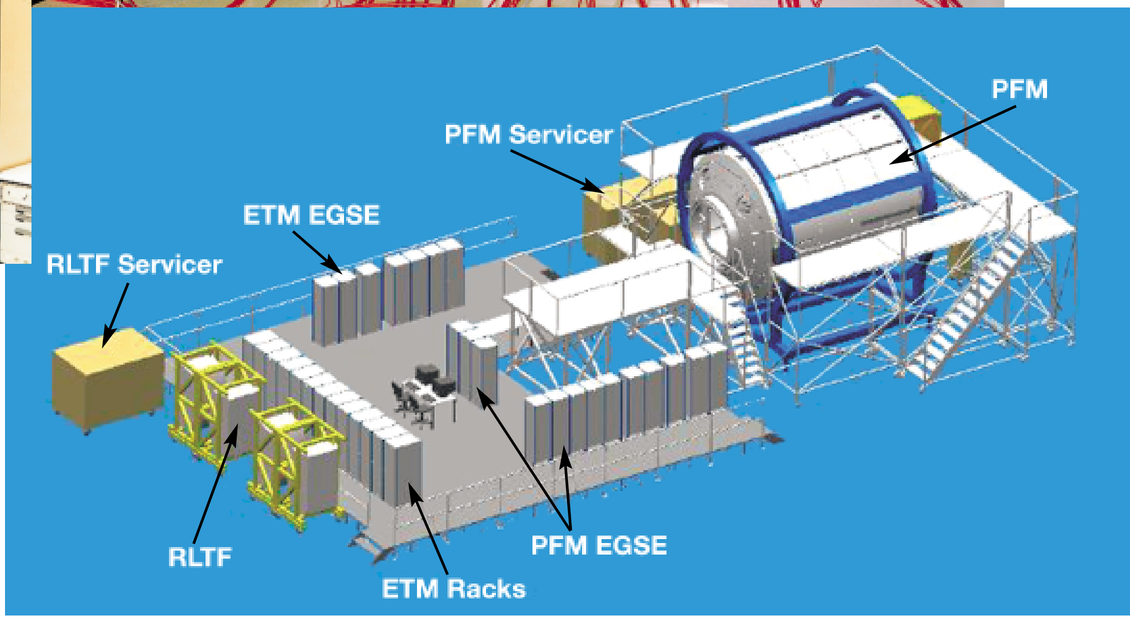


Fig. 24. The Columbus Electrical Test Model. The ETM racks are the dark cabinets in the background of the main photograph, seen in full in the small inset picture. The lighter cabinets are the EGSE racks.

- a reworking of the Emergency, Warning and Caution concept, and the addition of Caution channels.

In addition, at that stage of the project, the External Payload Facility was added to Columbus. The EPF was not in the original baseline because ESA had hoped to use other Station capabilities – either NASA's Express Pallets or Japan's Exposed Facility. However, the utilisation cost of the NASA real estate proved to be prohibitive, and the NASDA facility is completely booked for the foreseeable future. It was therefore decided to extend the Columbus capability.

The combination of the safety-related changes and EPF's introduction led to a Configuration Review of the Columbus mechanical system design in order to evaluate the implementation of these post-PDR differences. This review successfully concluded in September 1998.

The project is now in a phase that features:

- functional system testing on the Electrical Test Model;
- equipment and subsystem Critical Design Reviews;
- building up a Qualification database on the equipment-level test results, the overall system analyses and those

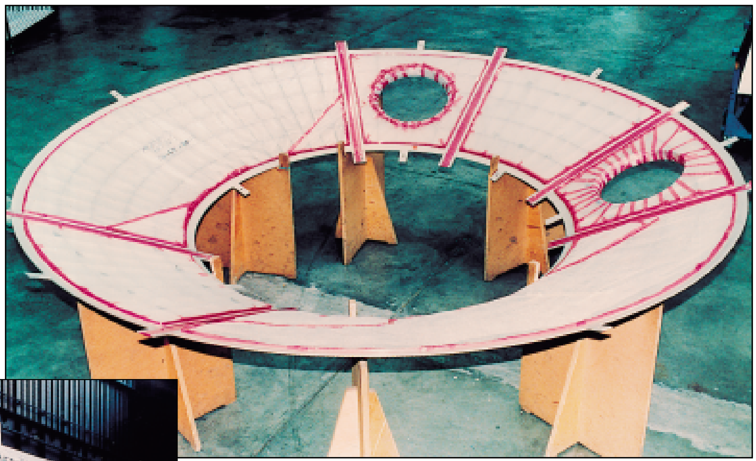
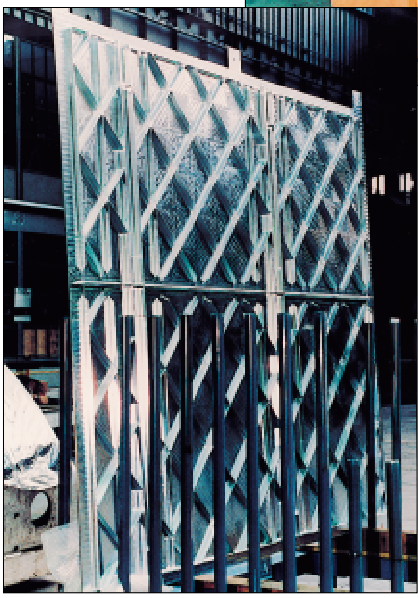


Fig. 25. Columbus Flight Model hardware under construction at Alenia Aerospazio in Turin. (Alenia)



requirements expected to be closed by a simple 'Review of Design'.

For the ETM tests, the Electrical Ground Support Equipment (EGSE) has been installed and connected to the ETM. An initial version of the system software has been integrated and the ETM testing began in May 1999. Fig. 24 shows the ETM in its test configuration.

Conduct of the unit- and subsystem-level CDRs is well under way. The campaign is ensuring overall design integrity and compatability with the lower level interfaces. Permission for equipment qualification/flight manufacturing is being released as these CDRs are completed. For mechanical system items (structure, thermal, harness, ECLSS, etc), CDR results are being integrated to generate the Pre-Integrated Columbus Assembly (PICA, at Alenia). The PICA-level CDR is planned for late in 1999. In the meantime, the Flight Unit's primary structure – a derivative of MPLM's primary structure and thus qualified by 'similarity' – is under construction. Welding on the cylinders and endcones began in May 1999. Fig. 25 shows part of the flight hardware.

The final/complete system Columbus CDR is planned for mid-2000, after the most critical ETM test results have been obtained and the lower level CDRs have been closed out.

Software Level
The Columbus onboard software is based on the Data Management System (DMS) software extended by other modules – such as laptop applications and flight automated procedures – to provide the end-to-end system functions.

By mid-1999, the DMS software was in a very critical phase: the baselined architecture was shown to be incompatible with the implemented data processing memory and speed. Whereas the computer memory shortage has been solved by memory upgrades, the limitation in central processing unit performance has necessitated extensive software changes. A review by external experts began in March 1999 to produce a solution with minimum programmatic impacts. The architecture has been changed and coded has restarted; qualified DMS software will be delivered in the spring of 2000.

Nevertheless, initial testing on the ETM can go ahead because the first tests cover only the most basic Columbus functions. The completion of ETM testing relies on the complete suite of software being available. Since the DMS software interfaces strongly with the other software modules, these may also be influenced, depending on the changes. This area of project development has priority.

Subsystem/Equipment Level
Different equipment has reached varying degrees of design maturity, ranging from 'PDR close-out' for the Payload Power Switching Box (a late arrival due to EPF's addition) up to 'CDR close-out' for many units, such as HUB and the Heater Control Unit.

Several unit pre-qualification tests have been successful, providing high confidence that the formal qualification tests on Qualification Models or Protoflight Models will be successful. The cabin ventilation qualification test was successful in February 1999, and the first of the fire suppression demonstrations was carried out in March 1999. The closed-loop performance of the module's whole water loop was tested in late 1998.

The Environmental Control and Life Support Subsystem (ECLSS) CDR began in January 1999. This review is in two parts. The first reviewed the subsystem-level test and analyses results, using data from the equipment developers. The second will be performed when the corresponding equipment-level CDRs are completed. Two of the units have had problems (in one case a contractor had to be replaced), so finalisation of the subsystem CDR will be achieved only after these are resolved.

The DMS CDR has had to be delayed because of the software incompatibility problems discussed above.

Project Difficulties and their Resolutions

As Columbus is but one element of the Station, there are many technical and operational inter-dependencies that are evolving concurrently with ESA's module. The interface design and verification therefore needs constant attention and thorough planning. An Interface Coordination Working Group (ICWG), co-chaired by NASA and ESA, routinely meets to define and refine the evolving interface definition, and to agree on the verification of the interface decisions. Incompatabilities arise no matter how closely this is tracked, and thus design changes and/or test changes have to be incorporated into the programme. A number recently occurred in the data management interface domain and in the testing of software transfer techniques. Such problems are an integral part of an international undertaking as vast as the ISS.

In some areas, the Columbus programme is at the cutting edge of technology. For example, in the design and verification of the Meteoroid and Debris Protection System (MDPS), the module's outer layer for shielding the crew and payloads from the hostile environment of low Earth orbit. The mathematics of damage prediction is not an exact science, and tests shooting particles at more than 10 km/s yield widely scattered results. The combined talents of European, American, Japanese and Russians experts in this field have yet to come up with a solution other than extreme conservatism. Columbus currently carries about 2 t of protection around its pressure shell.

In other areas, the programme has been used to trigger the 'Europeanisation' of technologies, rather than continuing to rely on other (generally American) sources. This has led to certain maturity problems. An example is the condensating heat exchanger, intended to control cabin humidity and based on the difficult technology of hydrophilic coating. The manufacturing processes – new for European industry – are very sensitive to contamination and a long-term solution has not yet been qualified. Another example is the cabin fan, which had acoustic noise and microgravity disturbance problems.

Moreover, the 'normal' project problems have also hit Columbus development – excess mass and insufficient computer memory capability, for example. Several changes ranging from material change to design modifications have had to be implemented to regain an adequate mass margin. The computer memory has been upgraded by adding RAM.

Utilisation and Facility Development

Columbus accommodates 10 internal International Standard Payload Racks and four External Payload Facility platforms. These are all shared equally by ESA and NASA for the whole duration of the ISS programme. Eight of the ISPRs are housed along the laboratory's sidewalls, with the remaining two in the ceiling area. (The rest of the rack locations are taken up with Columbus subsystem equipment or overall Station stowage space, for which three racks are allocated.) Each ISPR and EPF location is provided with power, data, video and cooling. Nitrogen purging and vacuum resources are available to the payload racks. The resources available at any one time are limited by the overall ISS capability, so resource timelining has to be developed, planned and executed.

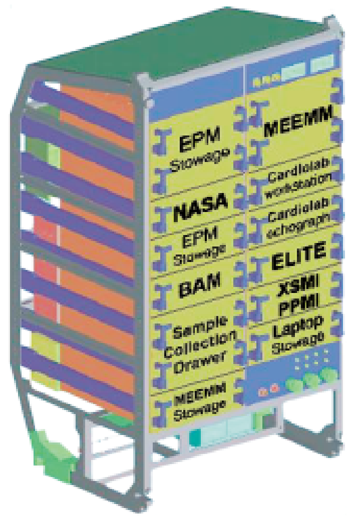
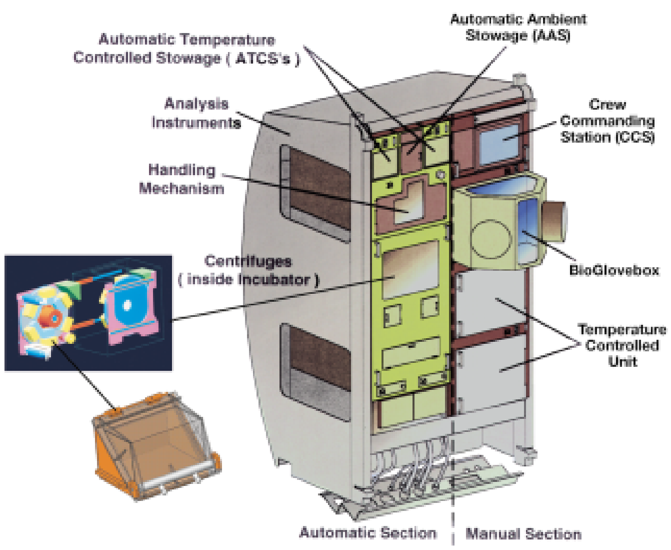


Fig. 27. EPM will support physiological research. (ESA)

The multi-purpose Columbus laboratory is designed to provide opportunities for all possible branches of space research, technology and exploitation, including:

- ◊ space biology,
- ◊ human physiology,
- ◊ material science,
- ◊ fluid science,
- ◊ space science,
- ◊ Earth observation,
- ◊ general physics,
- ◊ technology development.



The payload complement operating at any one time will be selected as a function of many variables, including: the type of payloads (such as pure research on the one hand, potential commercial applications on the other), the level and duration of resources required (crew time, power, data, etc), and their origin (are they from a Participating State?). Also taken into account will be the general merit of the payloads in scientific and/or application terms, and how they can be packaged as a compatible complement.

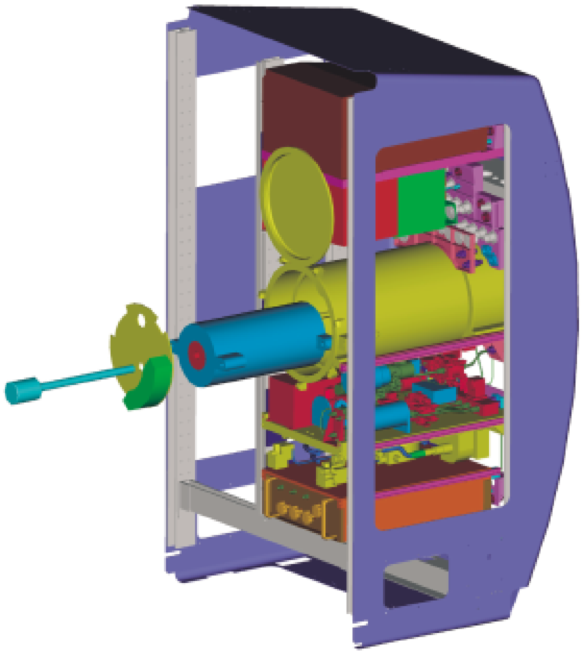
Numerous payload facilities are being developed in parallel with the Columbus laboratory development, for

Fig. 26. Biolab will support biological research. (ESA)

Fig. 28 (top): the Material Science Laboratory will investigate solidification physics, crystal growth with semiconductors, thermophysical properties and the physics of liquid states. (ESA)

Fig. 29 (centre): The Fluid Science Laboratory will study fluid behaviour in the absence of gravitational effects. (ESA/Ducros)

Fig. 30 (bottom): The European Drawer Rack provides a modular capability for sub-rack payloads. (ESA)

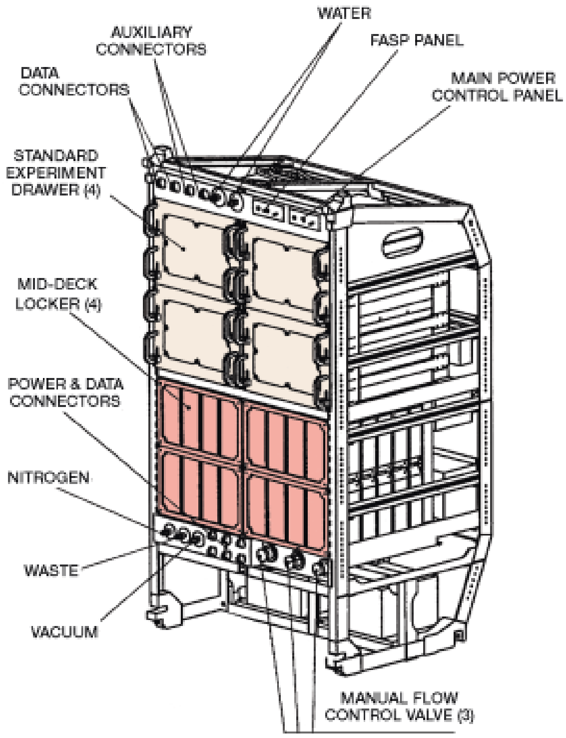


use both inside and outside the module. These include:

- Biolab (Fig. 26): a rack supporting biological experiments on microorganisms, animal cells, tissue cultures, small plants and small invertebrates in zero gravity. This is an extension – as for so many other payloads – of pioneering work conducted on the Spacelab missions;

- European Physiology Modules (Fig. 27): a rack dedicated to studying body functions in zero gravity, such as bone loss, circulation, respiration, organ and immune system behaviour, and their comparison with 1 g performance to determine how the results can be applied to Earth-bound atrophy and age-related problems;

- Material Science Laboratory (Fig. 28): a rack for research in solidification physics, crystal growth with semiconductors, measurement of thermophysical properties and the physics of liquid states. For example, crystal growth processes aimed at improving ground-based production methods can be studied. In metal physics, the influences of magnetic fields on microstructure can be determined. Microstructure control during solidification could lead to new materials with industrial applications;



- Fluid Science Laboratory (Fig. 29): a rack for studying the complex behaviour in instabilities and flows in multiphase systems, their kinetics as a function of gravitational variation, and the coupling between heat and mass transfer in fluids, along with research into combustion phenomena that should lead to improvements in energy production, propulsion efficiency and environmental issues;

- Numerous external facilities, such as:
  Atomic Clock Ensemble in Space (ACES), providing an ultra-accurate global time-scale, thereby

Fig. 31. Columbus also offers four External Payload Facility platforms. (ESA/Ducros)

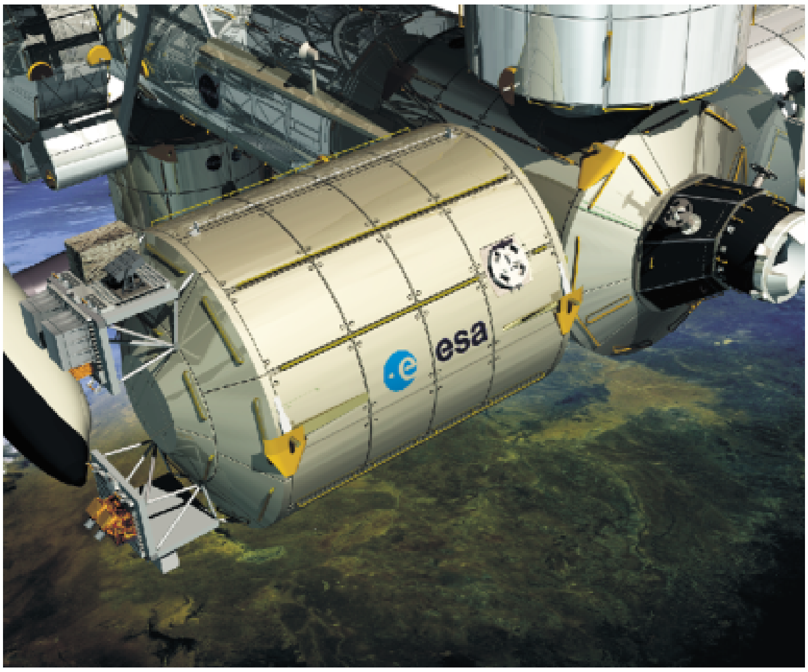


Fig. 32. ESA's Erasmus User Centre provides support to potential and active Space Station users. (ESA)

supporting precise evaluations of relativity;

Expose, mounted on the Coarse Pointing Device (CPD), to support the long-term studies of microbes in artificial meteorites and different ecosystems;

FOCUS, an infrared detection system to discover and track vegetation fires and volcanoes;

Solar Monitoring Observatory (also mounted on the CPD), to measure the Sun's total and spectral irradiance;

Technology Exposure Facility (TEF), an infrastructure providing for a wide range of on-orbit technology investigations.

To provide user information and eventually to support experiment development and operations, the Erasmus User Centre (EUC) was inaugurated at ESTEC in June 1999.

Ground Segment and Training

In the same way that Columbus is an integral part of a total ISS system, its ground segment is part of a bigger whole. The core of the ESA ground segment is the Columbus Control Centre, a facility at DLR's German Space Operations Centre (GSOC) in Oberpfaffenhofen. This centre will be the direct link to the on-orbit infrastructure; it will handle the Columbus module's command and control, and participate in planning and timelining Columbus orbital activities. It will be the interface to the de-centralised User Centres, which will have direct access to the payloads under their responsibility. It will also be the interface to the overall Space Station Control Center (SSCC) at NASA Johnson in Houston, Texas and the Payload Operations Integration Center (POIC) at NASA Marshall in Huntsville, Alabama, ensuring compatibility between Columbus and the rest of the infrastructure, as well as with the many simultaneous payload investigations.

The Columbus Control Centre will operate under the supervision of a management team, and will provide the real time operational decisions. It will have engineering and logistics support and the support of the European Astronauts Centre (EAC). The EAC organises and conducts crew training for Columbus operations, operates the medical facilities in support of crew health and oversees the general well-being of ESA crews and their families.

Training mock-ups representing the functional characteristics (and the physical interior) of the Columbus laboratory are being developed – a complete and high-fidelity mock-up for EAC and a simpler one for the Space Station Training Facility (SSTF) at NASA Johnson. The architecture for this crew trainer is shown in Fig. 33.

The initial payloads will be launched with Columbus, having been checked out with the module before leaving the ground. As time passes, new racks will be added and these will also need to be verified as compatible with the Columbus system. For this, the Rack Level Test Facility is being developed to simulate the on-orbit and ground segments, as well as the characteristics of the other payloads housed within the module, so that the new rack can be thoroughly tested. To maximise the cost-effectiveness of this RLTF, and to ensure the fidelity of its simulation, the check-out equipment will re-use the Electrical Test Model on which Columbus itself will have been verified. Fig. 34 shows a schematic of the RLTF.

During the Station's operational phase, all the ground segment and the on-orbit infrastructure will be connected by a multi-national communications system (a simplified block diagram is shown in Fig. 10). Command of the laboratory and its payloads will be via the Columbus Control Centre and the Interconnection Ground Subnet (IGS) central node through NASA's Tracking and Data Relay Satellite System to the ISS receivers. All safety-related command and control will go through the Space Station Control Center in Houston to ensure the centralised control of safety actions.

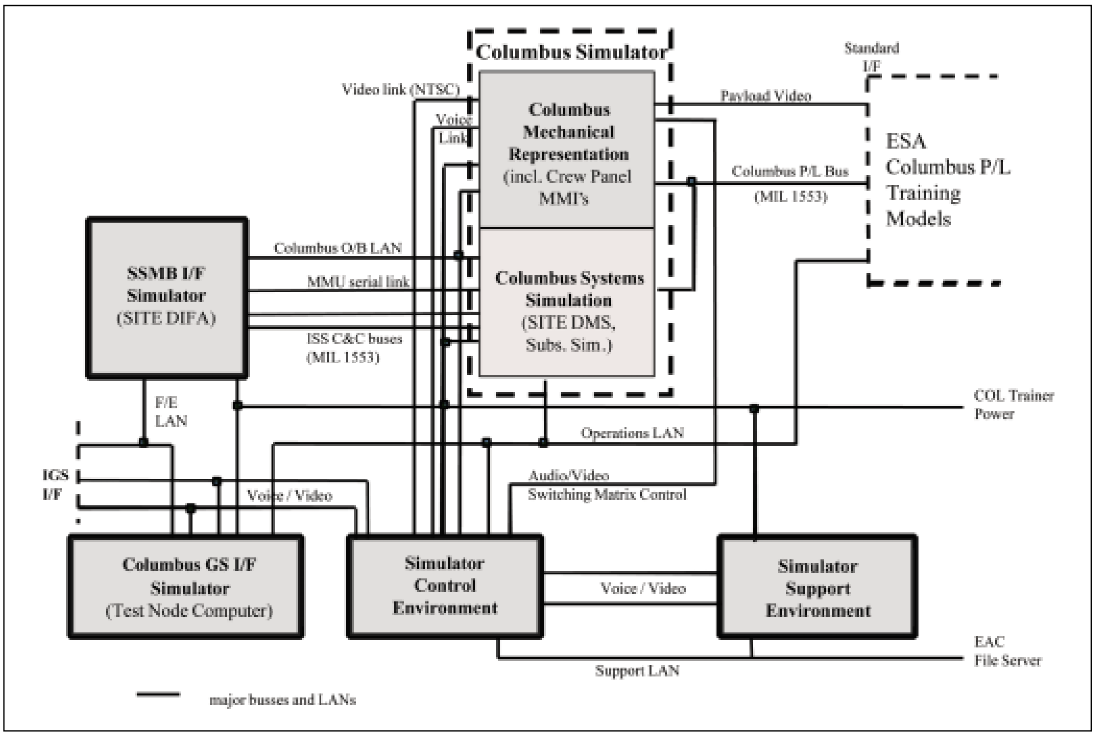
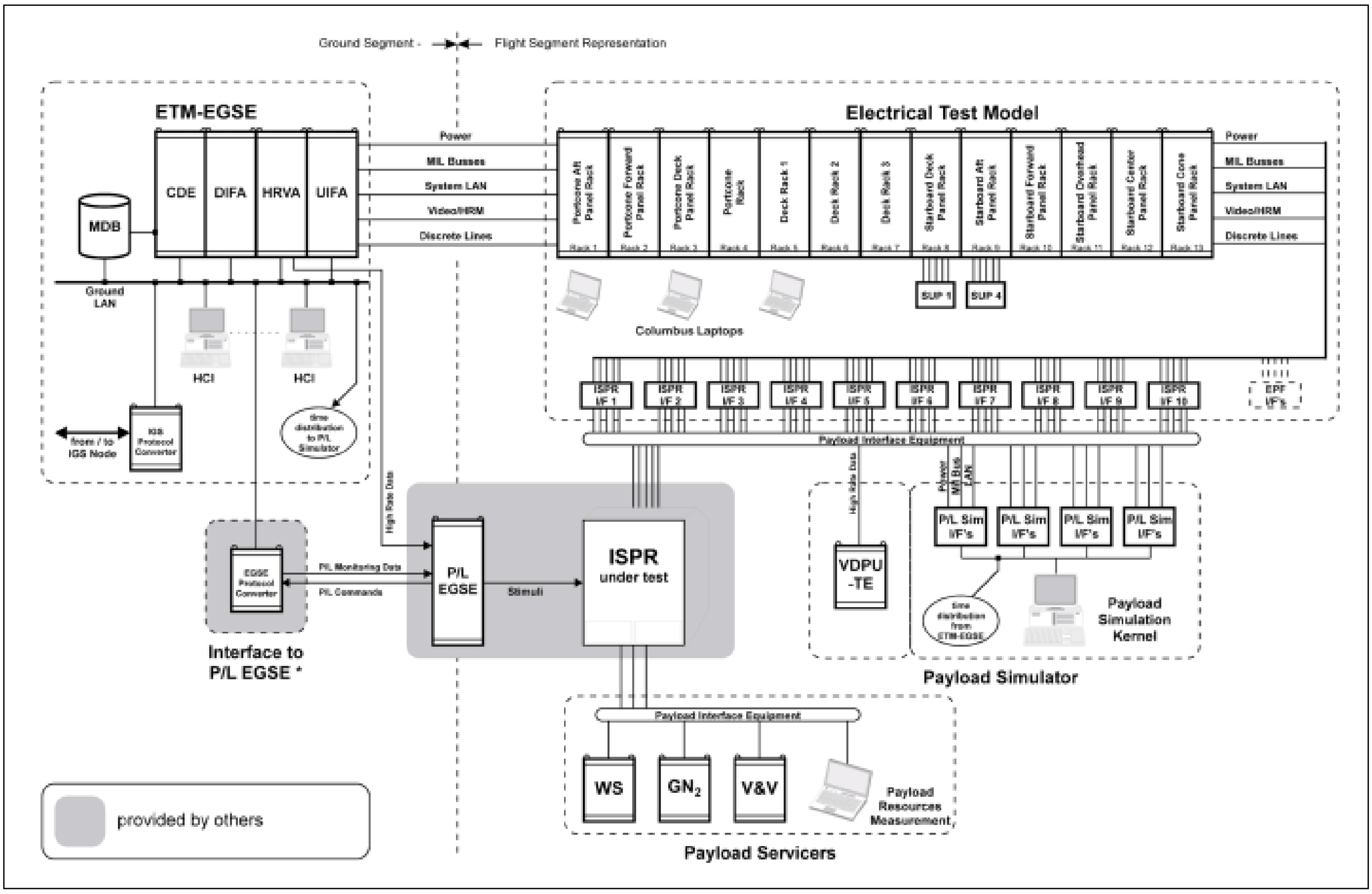


Fig. 33. The architecture for the Columbus crew trainer as part of the Space Station Training Facility at NASA Johnson. (ESA)

Fig. 34. The Rack Level Test Facility (RLTF). (ESA)



Downlinks will be available via TDRSS and the ESA Artemis / Japanese Data Relay and Test Satellite system, which will form a constellation early next century.

The Station's composite data stream routed via TDRSS will be sent to the Payload Data Service System (PDSS) at NASA Marshall for demultiplexing into 'Element' virtual channels. The ESA relay at Marshall will separate out the Columbus data and make it available to the Columbus Control Centre and the User Centres via the IGS central node.

Columbus Launch and ISS Assembly Sequence

During Phase B, it had been planned to launch the Columbus module on an Ariane-5. However, before programme approval, the Design-to-Cost requirement dictated that the module should be downsized to a 4-rack-long configuration so that its primary structure could be derived from ASI's MPLM. (This avoided the design and qualification cost of a dedicated new structure, saving tens of millions of Euros.) The MPLM, though, was designed and qualified for launch on NASA's Space Shuttle, which therefore became the baseline for Columbus. By the time Columbus was approved, at the Toulouse Ministerial Council in 1995, the overall ISS Assembly Sequence was already established, so the Columbus launch was set at the end of the sequence. It has since been advanced somewhat in the sequence, but it remains the last of the non-Russian laboratory modules to be attached.

There have been problems in beginning the Assembly Sequence, owing to various technical and financial problems of some of the other Partners. The first launch, of the US-financed Russian 'Zarya' module, finally took place in November 1998, closely followed by NASA's 'Unity' Node-1 a month later. A logistics flight was performed in May 1999, but the next element to be attached is Russia's 'Zvezda' Service Module, planned for early 2000, some 9 months later than expected.

The first permanent crew will enter the Station in early 2000 and by mid-2000 the first dedicated payload module – the US Laboratory 'Destiny' – will be launched, closely followed by an MPLM with its payload racks, thereby enabling the first utilisation activities to begin in the second half of 2000.The effects of the initial delay, and the further delay in the Service Module's appearance, has meant that the launch of Columbus is now planned for early 2004.

Conclusions

It took a long time for the International Partners, including Europe, to formalise their participation in the construction and operations of the International Space Station, and many years of paper studies, iterations and unfulfilled programme starts were expended. However, since the end of 1995, the implementation of European involvement has gathered significant momentum, and Columbus, the cornerstone of the participation, is at the vanguard of this progress.

The module is now well into the hardware phase: flight model items are under construction, qualification tests are underway and the design is baselined. Columbus has accumulated the normal number of development problems expected of any complicated spacecraft, but none is insurmountable. Its completion schedule is well ahead of the planned launch date.

The ground segment is also under implementation, utilisation plans are in place and the first experiments are being developed. The entire European manned space community is looking forward eagerly to starting its new, on-orbit, adventure.