Status of the Advanced Closed Loop System ACLS for Accommodation on the ISS

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The Advanced Closed-Loop System (ACLS) is a regenerative life support system for closed habitats. With regenerative processes the ACLS covers the life support functions of CO_2 removal, Oxygen generation and CO_2 Reprocessing. ACLS will be accommodated in the Destiny module, which offers all interfaces needed for extended operations. The NASA System Maturation Team has recommended operating ACLS for a period of one year to evaluate the value of ACLS technologies for future exploration missions. A form-fit-function FM-like Engineering Model (EM) was completed and served for validation of applied processes and associated control software ahead of its application for flight model operations. The EM is being integrated into the Ground Segment (GS) infrastructure in support of flight ops including maintenance procedures' validation. The ACLS Flight Model was completed and in environmental testing until end of 2016. Subsequent safety testing served for hazard control verification in support of the phase III Safety Review confirmed for end of April 2017. The paper summarizes the development and hardware status in support of the launch of the ACLS FM with HTV7 that is today envisaged for February 2018. Besides, the paper addresses the potential enhancement of ACLS to an ACLS Mk-II preparatory to exploration missions in LEO and beyond.

Nomenclature

ACLS	=	Advanced Closed Loop System
AFP	=	ACLS Front Panel Box
ASC	=	ACLS System Controller
CAM	=	Commercial, Aviation, Military
CCA	=	CO_2 Concentration Subsystem
CFU	=	Colony Forming Unit
COL	=	Columbus Module
COTS	=	Commercial Off The Shelf
CRA	=	CO_2 Reprocessing Subsystem
DAU	=	Data Acquisition Unit
ECLS	=	Environmental Control & Life Support
EM	=	Engineering Model
EUs	=	Electronic Units
FM	=	Flight Model
FAE	=	Fixed Alkaline Electrolyser
HTV	=	H-II Transport Vehicle
H/W	=	Hardware
I/F	=	Interface
ISPR	=	International Standard Payload Rack
IMI	=	Intermediate Maintenance Item
ISS	=	International Space Station
LLI	=	Life Limited Items
MAIT	=	Manufacture, Assembly, Integration & Test
MDP	=	Maximum Design Pressure
OGA	=	Oxygen Generation Subsystem
PIA	=	Payload Integration Agreement
P/L	=	Payload
PSM	=	Power Supply Module
PWB	=	Potable Water Bus
SCS	=	Stack Current Source
SMT	=	System Maturation Team
SRP	=	Safety Review Panel
STE	=	Special Test Equipment
S/W	=	Software
TBC	=	To Be Clarified
TBD	=	To Be Defined / To Be Determined
THC	=	Temperature and Humidity Control
WMS	=	Water Management Subsystem
WWB	=	Waste Water Bus

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I. Introduction

The Advanced Closed-Loop System (ACLS) is a regenerative life support system for closed habitats. With regenerative processes the ACLS covers the life support functions of CO_2 removal, oxygen generation and CO_2 reprocessing. After many years of predevelopment which has been reported regularly at ICES the ACLS project has started into full development in 2011. ACLS will be qualified as non-mission critical system hardware. It is foreseen to be launched on HTV7 in February 2018.

In the past the NASA System Maturation Team (SMT) has evaluated the merits of ACLS technologies, which differ from the ones presently applied on ISS. The final recommendation was that: “the SMT would like to see the ACLS operated for a minimum of 1 year (cumulative) on ISS to prove reliability for future exploration missions.” In view of above identified launch date one year of cumulative operation of ACLS onboard the ISS is envisaged to be achieved until the end of 2019.

Following the SMT recommendation details and a series of technical and programmatic discussions it was decided to move ACLS from the Columbus module to the LAB1P1 location in the Destiny module. This location had been used for the early demonstration of NASA’s Oxygen Generation System and contains a potable water interface, a dedicated hydrogen vent line and two-way access to the waste water bus. In addition to the operational savings the continuous availability of all resources allowed for a simplification of the ACLS internal Water Management subsystem. In consequence to the Payload Integration Agreement (PIA) on subject between the European Space Agency and NASA an Interface Control Document (ICD) on ACLS - in NASA's nomenclature the 'Life Support System LSS' - in Destiny Module accommodation is put in place, accordingly.

II. ACLS Functional Description

ACLS is a system which can recycle oxygen from the CO_2 that is produced by astronauts in manned space vehicles. Such recycling technology can reduce the re-supply to the ISS significantly. On longer duration missions like a lunar base or a manned mission to Mars closed loop (regenerative) systems will be essential to make such missions feasible. ACLS has three major functions:

(1) The CO_2 Concentration Subsystem (CCA) concentrates the CO_2 from the cabin and thus controls the CO_2 level to acceptable levels;

(2) In the CO_2 Reprocessing Subsystem (CRA) or Sabatier reactor, hydrogen and CO_2 react over a catalyst to form water and methane. The water is condensed and separated from the product gas stream and fed back to the ACLS Water Management system;

(3) The Oxygen Generation Subsystem (OGA) is a Fixed Alkaline Electrolyser (FAE) which splits water into its constituents: oxygen and hydrogen.

Methane (CH_4) is vented overboard. Based on this process about 40% of the water needed for oxygen production can be produced on-board from the CO_2 which is exhaled by the astronauts. The remaining water needs to be uploaded from ground.

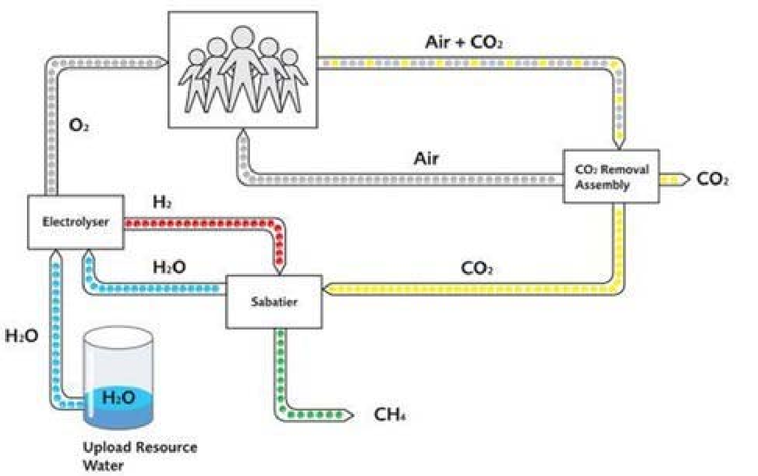

Figure 1: ACLS Closed Loop Schematic

Sized for a crew of 3 the operation of the ACLS on-board the ISS can save up to 450 kg of water upload per year.
In full operating mode ACLS will:

- Remove 3 kg/day of CO_2
- Produce 2.5 kg/day of O_2
- Produce 1.2 kg/day of liquid water from the reaction of hydrogen and CO_2.

The ACLS closed loop cycle is shown in Figure 1.

III. Evaluation of ACLS against NASA Exploration Needs

In preparation for future exploration missions the NASA SMT has drawn up a list of exploration needs for various subsystems. ACLS has been evaluated against the needs for future systems. The SMT results can be summarized as follows:

A. CO_2 Removal Function

ACLS main advantage is the use of the adsorbent Astrine™, a solid amine resin, which has a high adsorption capacity even at very low CO_2 levels in the cabin air. Although the design point of ACLS is at 4 mbar CO_2 (3 mmHg) the ACLS CCA Subsystem can be operated at lower CO_2 concentration levels. The exploration goal would be to maintain a cabin air concentration of < 2.7 mbar (2 mmHg) $ppCO_2$.

B. Oxygen Generation Function

The comparison of ACLS against the exploration needs for oxygen generation underlines the strength of the Fixed Alkaline Electrolyser (FAE) technology, which has no moving parts and therefore has few life limited items. Including new gas sensors for oxygen and hydrogen with a lifetime of up to three years, the same as the electrolyser stack, the predicted upload for ACLS OGA is already in the range of the exploration need as defined by the NASA SMT.

C. Exploration Needs for CO_2 Reprocessing

The two-stage Sabatier reactor of ACLS is more efficient than presently used one-stage systems. It offers a high hydrogen conversion. However, due to the limitation of the Sabatier reaction at an educt ratio R_H_2/CO_2 = 2.3 it can recycle only about half of the oxygen from CO_2. The goal of 75% oxygen recovery can be reached only with additional or differing technologies. Therefore, ACLS has been equipped with an additional interface which allows routing of excess CO_2 to an add-on external experiment. Specifically, today it is envisaged that in course of its operation onboard the ISS till the end of 2019 ACLS shall supply excess CO_2 to the ISS / PhotoBioReactor (PBR) Experiment Payload of the German Space Agency (DLR).

IV. ACLS Installation in the Destiny Module

An Interface Control Document (ICD) was elaborated between ESA and NASA for ACLS integration in the Destiny Module. The design of the external ACLS interface is presented on figure 2.

The feasibility of installing and operating ACLS in Destiny had been evaluated positively. One point of discussion had been the impact of ACLS on ISS Temperature and Humidity Control (THC). ACLS uses steam for desorbing CO_2 from the solid amine adsorbent ASTRINE™. The steam is produced from waste water which is processed internally by ACLS. The steam condenses during CO_2 desorption in the adsorbers and is subsequently released during the following adsorption cycle. The released humidity is partially recovered in an ACLS internal condensing heat exchanger; the remainder is released to the cabin from where it will be collected in the ISS Temperature and Humidity Control subsystem. An exchange of telemetry data between the ACLS Operations Team and the NASA ETHOS Group is foreseen to optimize the ACLS operation inside Destiny.

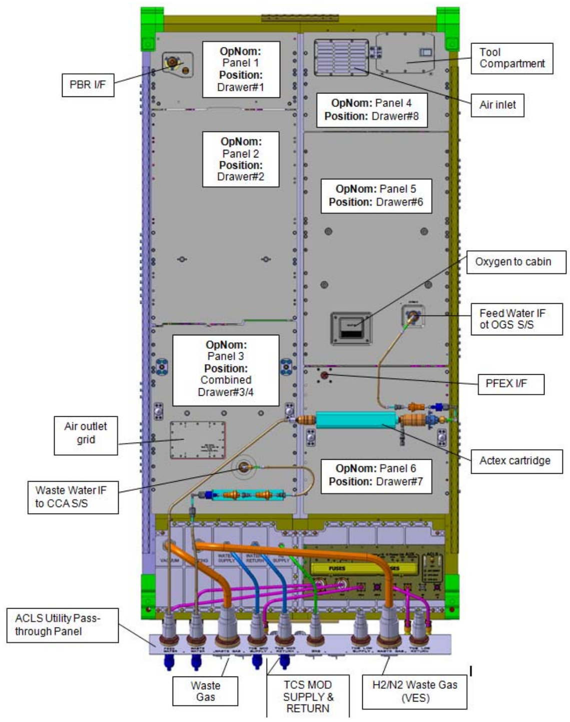

Figure 2: ACLS Interfaces and Front Panel Equipment

ACLS fits in the available power and cooling resources of Destiny which will be available at the time of launch. As ACLS has its own system controller, only data handling and commanding will be routed via the US Payload LAN. ACLS will make use of the TreK interface which allows for data and command routing. Monitoring and commanding of ACLS will be done from Airbus premises in Friedrichshafen with major status data being shared with NASA and ESA Control Centers, as applicable. ACLS in-orbit commissioning period will last about four weeks, followed by operation on request as back-up respectively complement to the other ISS life support systems, in close coordination with ETHOS.

V. ACLS Design

A. ACLS Rack

ACLS is located in an International Standard Payload Rack (ISPR). The subsystems are located in drawers which allow easy access to components for preventive and corrective maintenance. All functional interfaces, electrical and fluidic are located at the backplane of the drawers with the exception of the process water supply interfaces. The drawer level interfaces employ automatic connectors.

On figure 3 a photograph of the ACLS FM rack with all drawers integrated and the front panels detached is presented. On Figure 4 the drawers' allocation in the ACLS Rack is identified.

Figure 3: FM Rack with all integrated Drawers (w/o closure panels)

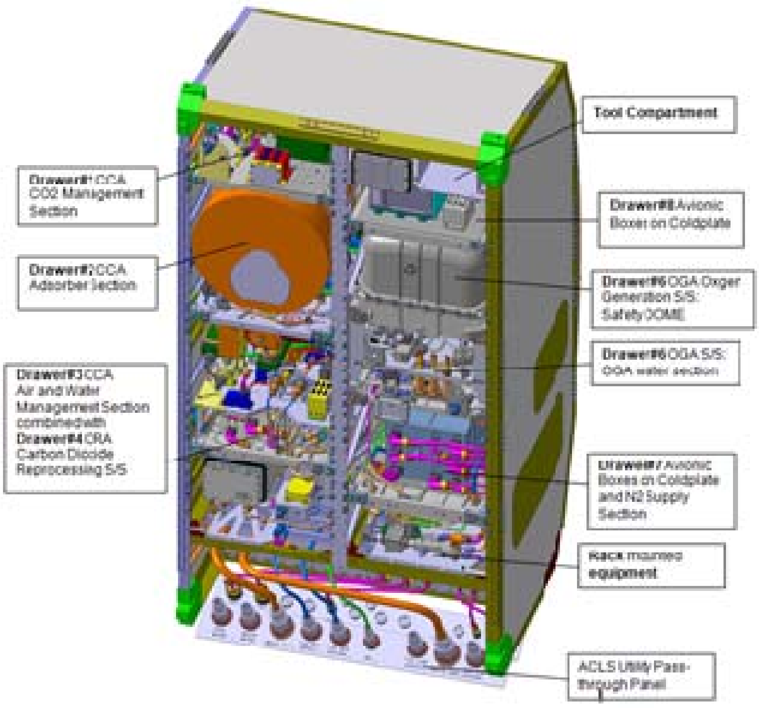

Figure 4: ACLS front view w/o Front Panels

B. CO_2 Concentration Subsystem (CCA)

The CCA is distributed over three drawers.

Drawer 1 contains the CO_2 Management Section; it receives the desorbed CO_2 and routes it either to the vent line or to the CRA subsystem. It includes pressure regulators and oxygen sensors: CO_2 is routed to the CRA only once its oxygen content is below 5% (CO_2 quality supervision) and the CO_2 flow rate is in a pre-defined range (CO_2 flow supervision using a mass flow meter). Drawer 1 is further equipped with a condensate pump, solenoid valves, sensors and harness. A cold plate takes up the heat dissipated by a CCA data acquisition unit located on the drawer. On figure 5 a photograph is shown of the populated FM drawer 1 comprising the CO_2 management section and equipment control electronics that are mounted on a cold plate.

Drawer 2 houses the three CCA adsorber beds, air plenums and air in- and outlet valves plus two CO_2 Water Recovery Units (WRUs) for drying CO_2 before venting or use in the CRA. Figure 6 does comprise a photograph of a single FM adsorber bed. Figure 7 does comprise photographs of the FM Drawer 2 - at the left - without the three single adsorber beds installed and - at the right - then with the single adsorber beds installed.

Drawer 3 contains the air and water management of the CCA: it consists of an air ventilation fan, which circulates cabin air through the adsorber beds, a condensing heat exchanger to limit latent heat release to the cabin from the adsorber beds after desorption and a centrifugal condensate water separator (common item from Columbus ECLS). The other part of the drawer is the Water Management Subsystem: a UV-LED unit to control microbes, a gas trap, a CFU filter and a buffer tank as well as pumps to transport the water.

Figure 5: FM Drawer 1 with CO_2 Management Section

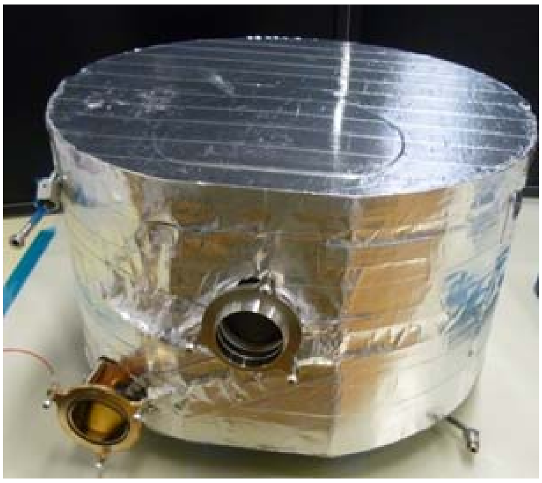

Figure 6: FM CO_2 Adsorber Bed

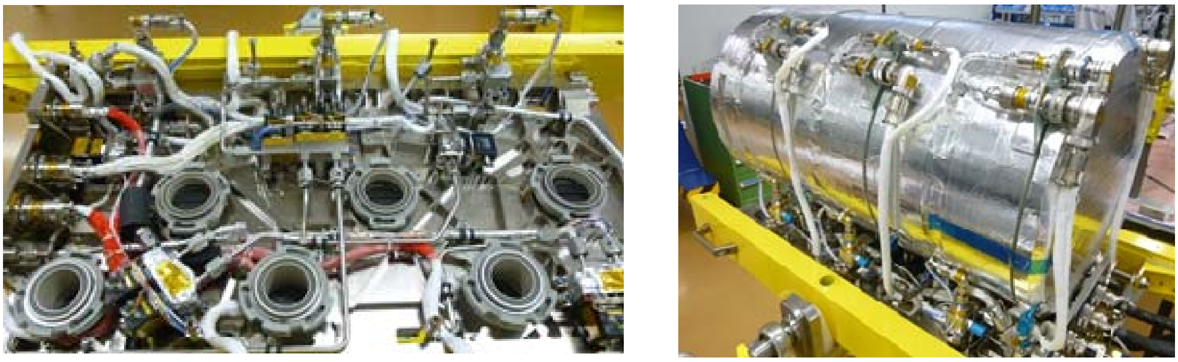

Figure 7: FM Drawer 2 w/o CCA adsorber beds (left) and fully integrated (right)

C. CO_2 Reprocessing Subsystem (CRA)

The CRA is located in **drawer 4**. The Sabatier reactor stages are covered by thermal insulation. The reactors are heated to its reaction temperature by electric heaters.

After the two Sabatier reactor stages the gases pass over a static condenser/water separator stage, which separates the product water. The other product, methane, and unreacted CO_2 are vented to space via the H_2/N_2 Waste Gas Line I/F.

The CRA reactors have been designed for CO_2 and H_2 gas flow rates for a crew of three. Tests with the CRA FM subsystem have confirmed the high hydrogen conversion of > 90% and a water production rate of 1.2 kg/day for the 3crew design point.

Figure 8 provides a photograph of the FM drawer 3 containing the air and water management of the CCA, with the FM drawer 4 comprising the CRA mounted on top of drawer 3. Figure 9 does comprise photographs of the FM Drawer 4 - at the left - top view of drawer carrying the Sabatier reactor section covered by dedicated insulation and - at the right - bottom view of drawer amongst others carrying the water recovery unit and the CRA Power Supply Module (PSM) mounted on a cold plate.

Figure 8: FM Drawer 3/4

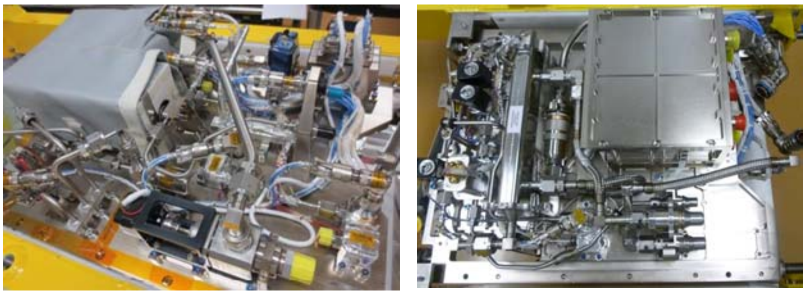

Figure 9: Drawer 4 top view (left) and bottom view (right)

D. Oxygen Generation Subsystem (OGA)

The OGA is located on **Drawer 6**. The major item is the electrolyser stack, which is located under a safety dome. The dome is evacuated and provides the third level of containment against leakage of gases and electrolyte to the cabin; the first two levels of sealing are integrated in the electrolyser stack. Inside the dome contains all pressurized gas components, like valves, pressure reducers and KOH filters, which protect downstream equipment against accidental release of electrolyte. Outside the dome oxygen is routed to cabin at ambient pressure while hydrogen is routed to the CRA subsystem at sub-ambient pressure.

The lower part of the drawer contains the OGA Water Loop and further auxiliary equipment. Due to ACLS integration into the Destiny Module and the availability of a Potable Water Supply I/F, the OGA Water Management Subsystem has been simplified to an I/F shut-off valve, check valves for MDP control and an I/F pressure sensor. For iodine removal an Actex cartridge is used, common to other ISS applications. The cartridge is located outside the rack at the front allowing for easy removal. In the Feed Water I/F flex line also a particle filter is integrated.

Figure 10 does comprise a photograph - top view - on populated FM drawer 6, with the safety dome cover detached, showing, at top, the 12 cell electrolyser stack including KOH filters covered by its dedicated insulation and, at bottom the supplementary equipment allocated inside the safety dome. On figure 11 - top - a photograph is given of one KOH filter branch, with foil heaters attached thereto and exclusive of its dedicated insulation. On figure 11- bottom - a photograph of the 12 cell electrolyser stack exclusive of its dedicated insulation is presented.

Figure 10: FM Drawer 6

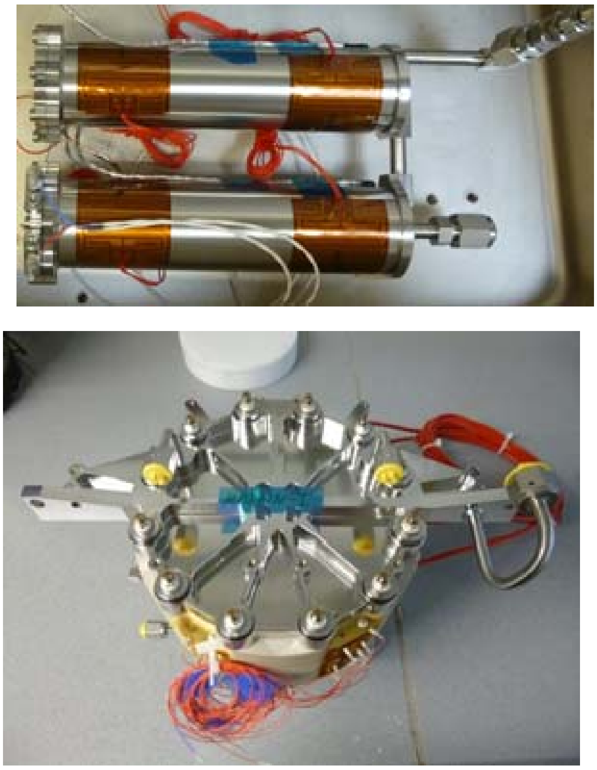

Figure 11: KOH Filter (Top) and Electrolyser Stack (Bottom)

E. Avionics Subsystem and Software

The ACLS avionics subsystem has a distributed architecture and therefore is located in different drawers.

Drawer 7 contains the heaviest items, the Stack Current Source for the OGA electrolyser and the CCA and OGA Power Supply Modules (PSMs). The Stack Current Source (SCS) also includes an Impedance Measurement function which serves for monitoring of the quality of the single cells of the 12 cell electrolyser stack.

Furthermore, Drawer 7 comprises an N_2 supply section that allows for purging of the electrolyser's water compartment ahead of system run-down.

Figure 12 - left - does comprise a view on the FM drawer 7 with its N_2 supply section whereas - right - such figure does provide a bottom view on FM drawer 7 carrying electronics boxes mounted on a cold plate.

The **Drawer 8** is located at the top of the rack and contains the ACLS System Controller (ASC) and the OGA Data Acquisition Unit (DAU).

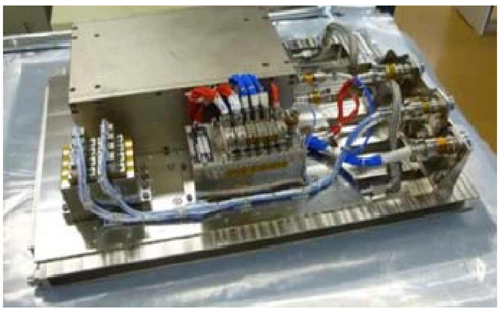

Figure 12: Avionics Drawer 7 incl. N_2 supply Section (left) and Avionics Drawer 8 (right)

VI. ACLS Integration & Test Status

The ACLS Engineering Model (EM) is fully integrated i.e. its subsystems were functionally tested and finally installed in an ISPR rack. EM Rack level testing was initially done with STE (Special Test Equipment) avionics and software. Subsequently, an EM system test campaign was done applying EM avionic boxes including the ACLS' dedicated system controller and software.

The ACLS Flight Model (FM) is fully integrated and was initially functionally tested prior to environmental testing. An environmental test program comprised of

- Modal Survey Test
- Vibration Test
- EMC Test
- Acoustic Noise Test
- Physical Properties

was completed by the end of 2016. Subsequent safety testing was done for hazard control verification in support of the phase III Safety Review confirmed for end of April 2017.

Figure 13 shows a photograph of the ACLS FM Rack in the Modal Survey Test configuration and associated test set-up environment.

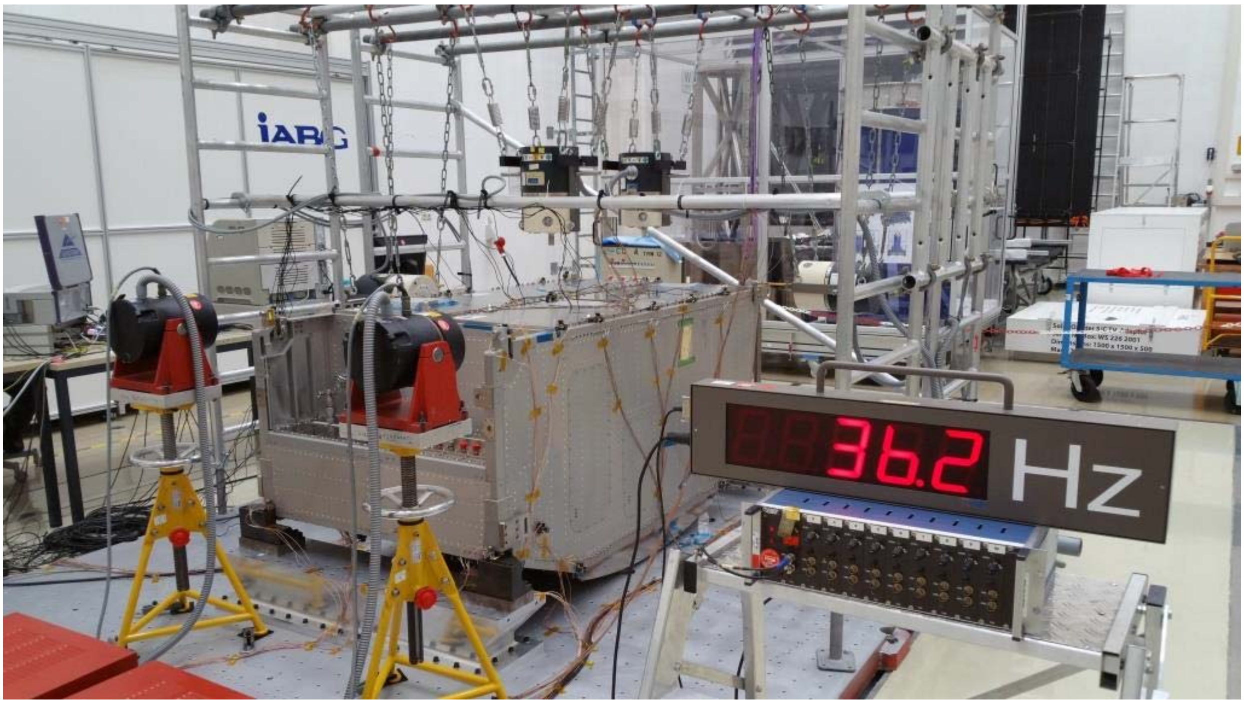

Figure 13: Rack level Modal Survey Testing (MST)

Figure 14 does comprise photographs of individual drawers being installed in the vibration test adapter for drawer level vibration testing, whereas the very right photograph shows a Cargo Transportation Bag (CTB) when applied for vibration testing of separate launch items, namely the single adsorber beds.

Figure 14: Vibration Testing (Drawer Level - integr. Launch Config. vs. CTB Level - separate Launch Items)

Figure 15 provides a photograph of the FM Rack in the ElectroMagnetic Compatibility (EMC) test configuration and associated test set-up environment.

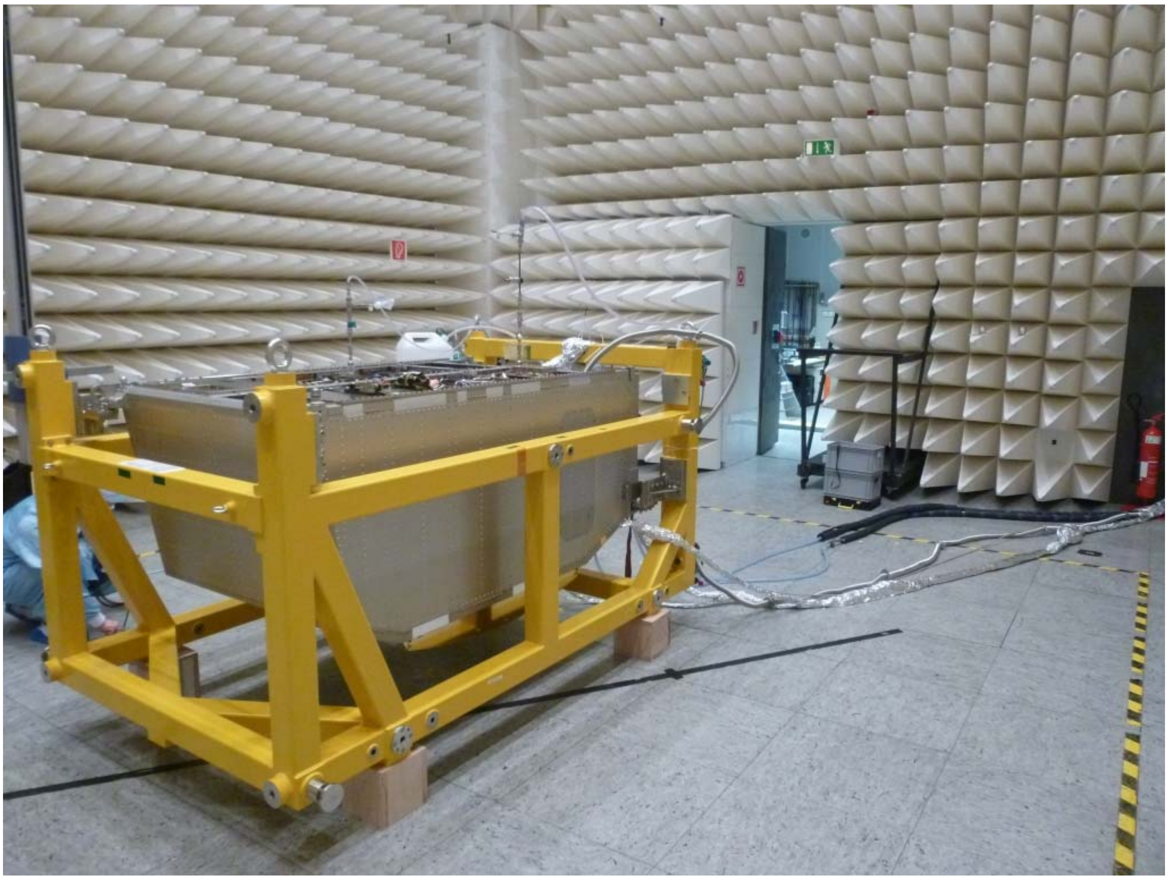

Figure 15: Rack Level EMC Testing

On figure 16 a photograph is given of the FM Rack in audible noise test configuration and associated test set-up environment.

Figure 16: Rack Level Audible Noise Testing

At the date of submittal of this paper the ACLS FM is installed in the system performance test bench as shown on the photograph comprised in figure 17. The remaining test program till ACLS FM transfer to launch site is comprised of

- Post environmental performance testing
- Interface testing then with the FM fluid supply / return lines installed
- Offgassing testing

Figure 17: FM Rack in System Performance Test Bench

VI. Outlook

ACLS has progressed well in terms of both, EM and FM system integration and test completion.

EM Subsystem testing is completed and EM system integration & testing with Avionics and S/W is completed to the level having allowed for S/W release for FM application.

FM system integration and pre-testing is completed and the FM was in rack level environmental testing and subsequent safety related testing in support of a conclusive data package that is compiled preparatory to the Phase III Safety Review scheduled for end of April 2017. The FM is installed in the test bench at AirbusDS and is subject to full-blown performance testing.

Furthermore, the development, installation and validation of the Ground Segment and associated ops products are well succeeding, including the compilation of relevant details for flight procedures.

Besides, in reply to further life support system needs when going beyond Low Earth Orbit, an ACLS Mk-II phase A study is in process

- to determine the operational flexibility of the ACLS 'as-built' configuration beyond its design point, and
- to develop, supported by breadboarding, the design of future ACLS Mk-II drawers for technology demonstration in the modular ACLS rack infrastructure.

Acknowledgments

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