41st International Conference on Environmental Systems
17 - 21 July 2011, Portland, Oregon

AIAA 2011-5076

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

Klaus Bockstahler[1] and Joachim Lucas[2]
Astrium GmbH, TO51, Friedrichshafen, Germany, 88039

Johannes Witt[3] and Daniele Laurini[4]
ESA-ESTEC, D/HSF, P.O. Box 299, 2200 AZ Noordwijk, The Netherlands

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:

(1) Removal of carbon dioxide from the spacecraft atmosphere via a regenerative adsorption/desorption process,
(2) Supply of breathable oxygen via electrolysis of water,
(3) Catalytic conversion of carbon dioxide with hydrogen to water and methane.

ACLS will be accommodated in an ISPR Rack which will contain all main and support functions like power and data handling and process water management. It is foreseen to be installed onboard the International Space Station (ISS) in the Columbus Module. After an initial commissioning phase ACLS shall be operated as a supplement of the ISS Life Support Subsystem thus enhancing its redundancy. Due to the regenerative processes applied in the ACLS it will allow a significant reduction of water upload to the ISS.

The development of ACLS as an ISS ISPR rack facility started with a Phase B in 2003. The latest phase C1 is finalised in May 2011. Subsequent Phase C/D/E actually being settled shall result in the ACLS being operable onboard the ISS starting in early 2016.

The paper summarizes the achieved status of design development and comprises an outlook on near-term development tasks subject to phase C/D.

Nomenclature

AAA = Avionics Air Assembly
ACLS = Advanced Closed Loop System
ARES = Air Revitalization System
ASC = ACLS System Controller
ATV = Automatic Transfer Vehicle
CAM = Commercial, Aviation, Military
CCA = CO_2 Concentration Assembly
COL = Columbus Module
COTS = Commercial Off The Shelf
CRA = CO_2 Reprocessing Assembly
DM = Development Model
EB = Elegant Breadboard
EDV/CWS = ISS Portable Water Container
EM = Engineering Model
EDR = European Drawer Rack
ETC = European Transport Carrier
FAE = Fixed Alkaline Electrolyser
GSTP = General Support Technology Programme
HoA = Heads of Agency
HTV = H-II Transport Vehicle
H/W = Hardware
I/F = Interface
IHI ISPR = Japanese International Standard Payload Rack
IMI = Intermediate Maintenance Item
ISS = International Space Station
LLI = Life Limited Items
MAIT = Manufacture, Assembly, Integration & Test
OGA = Oxygen Generation Assembly
P/L = Payload
RFCS = Regenerative Fuel Cell System
SCS = Stack Current Source
SDA = Smoke Detection Assembly
SPOE = Standard Payload Outfitting Equipment
SRD = System Requirements Document
TBC = To Be Clarified
TBD = To Be Defined / To Be Determined
WMS = Water Management Subsystem

---

[1] ACLS Program Manager, Energy and Life Support Systems
[2] System Engineering Lead & Expert, Energy and Life Support Systems
[3] Senior Life Support Engineer
[4] Head of ISS Infrastructure Division

I. Introduction

During the last years there has always been a paper on the development progress of ACLS (formerly ARES) on the ICES conferences, see references [1] to [3] for latest papers. For the new reader this introduction summarizes the background behind ACLS. In addition the ACLS requirements stipulated by ESA's latest SRD on subject are outlined.

A. 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 Assembly (CCA) concentrates the CO_2 from the cabin and thus controls the CO_2 level to acceptable levels;

(2) In the CO_2 Reprocessing Assembly (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 electrolyser;

(3) The Oxygen Generation Assembly (OGA) is an electrolyser which splits water into its constituents: oxygen and hydrogen.

Methane (CH_4) is vented overboard. In this way about 50% of the water needed for oxygen production can be produced onboard from the CO_2 which is exhaled by the astronauts. The remaining water needs to be uploaded from ground.

Nominally the ISS inhabits a crew of six. In order to produce oxygen for this crew more than 2 tons of water is needed per year. This will put an important strain on logistics flight especially once the Space Shuttle is retired in 2011. Sized for a crew of 3, the operation of the ACLS onboard the ISS will save about 450 kg of water upload per year.

The ACLS cycle is shown on Figure 1.

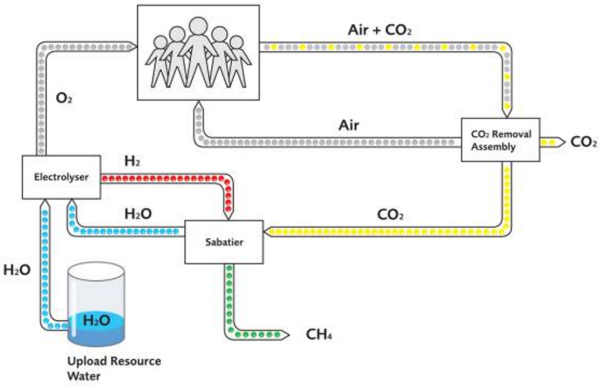


Figure 1. Closed Loop System with ACLS

The Sabatier reactor is the key element for closing the oxygen loop. The Sabatier is a catalytic reactor which reacts H_2 and CO_2 at elevated temperatures to water and methane (CH_4). The water is fed into the electrolyser for reclaiming the O_2 and closing the oxygen loop. At this stage the by-product methane (CH_4) is of no further use and is vented overboard. Closing the H_2 loop will become a future development step towards ACLS application for human exploration mission building blocks, see reference[4].

B. ACLS Requirements Outline

The major i.e. driving requirements applied on ACLS design development are as follows:

(a) ACLS shall be launched as a fully integrated (IHI) ISPR rack in the pressurized compartment of the HTV and then be installed and operated in the Columbus module preferably at A1 Rack position;

(b) ACLS shall be designed for in-orbit maintenance thus comprised of exchangeable Intermediate Maintenance Items (IMI) that shall be compatible with launch on all available ISS resupply vehicles;

(c) ACLS shall have a design life of 10 years through preventive and corrective maintenance; ACLS life limited items shall be designed for an on-orbit operational lifetime of minimum 3 years;

(d) ACLS shall be designed for a minimum of 50 on/off cycles per year in orbit.

(e) in continuous operation ACLS shall remove at least 3 kg/day CO_2 from the cabin air at a nominal CO_2 level of 4 hPa;

(f) in continuous operation ACLS shall generate at least 2.52 kg/day O_2 by the electrolysis of water;

(g) in continuous operation ACLS shall generate at least 1.2 kg/day of liquid water from the reaction of Hydrogen and CO_2;

(h) in continuous operation ACLS shall limit the loss of cabin air through the external ventline to $\leq$ 50 g/day;

(i) in continuous operation ACLS shall limit the loss of water vapour through the external ventline to $\leq$ 90 g/day (tbc);

(j) ACLS shall provide an interface to the Columbus condensate line for the supply of feed water and for the rejection of product water; ACLS shall provide interfaces to water bags for supply of potable water and condensate supply/rejection.

(k) for the venting of waste gases ACLS shall provide an interface to the Columbus P/L ventline that shall be permanently available to ACLS during its operation.

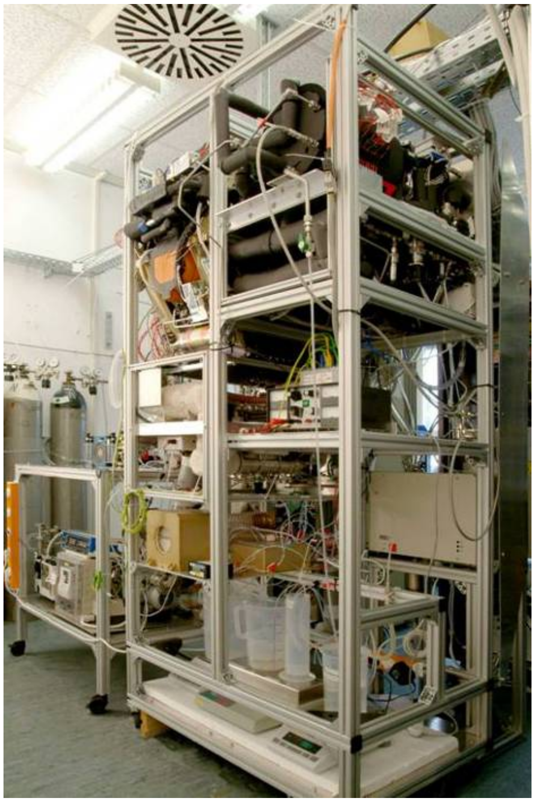


Figure 2. Photo of the ACLS Elegant Breadboard

C. Summary of Major Activities since latest ACLS Status Paper

The major activities performed since the last ACLS status paper[3] are related to

- ACLS System Level:
  - further system design development & Rack accommodation supported by analyses and testing as input to phase C/D kick-off;
- CCA CO_2 Adsorber Subsystem Level:
  - CCA performance testing with 1-bed Adsorber Engineering Model supported by EcosimPro Modelling; definition of fan performance requirements
  - Lifetime Testing with CCA Steam Generator and with Adsorbent Resin ASTRINE™
- OGA Electrolyser Subsystem Level:
  - OGA stack component detailed design development and validation through testing (perforated disc, membrane, seals) with further emphasis on electrolyser application in regenerative energy system
  - operational parameter variation - sensitivity testing (min/max parameter operation)
  - FAE electrolyte (KOH) adsorption & contamination testing (CO_2 and alcohol in process water)
- CRA Sabatier Subsystem Level:
  - Establishment of reactor section procurement specification
- WMS Water Management Subsystem Level:
  - Initial trade-off on suitable water treatment & quality monitoring technologies
  - Assessment of process water balance in support of trade-off on water supply alternatives
- Avionics Subsystem Level:
  - Development of avionics architecture and its accommodation in Rack
- ACLS Component Level:
  - development of CAM/COTS Items (H_2, O_2 Sensors, Absolute and Differential Pressure Sensors, KOH Filter) and definition of requirements for ventline pressure control section & related components

II. ACLS Design Status

In phase B that was completed in late 2008 extensive system level testing had been done with an Elegant Breadboard (EB) of the ACLS, see above Figure 2, covering all three functions i.e. CCA, CRA and OGA. Throughout phase C1 completed in May 2011 further testing was done on both, subsystem and equipment level.

System, subsystem and equipment level test results evaluation, together with the requirements being baselined in the SRD, see previous chapter B, serve as the valid input for ACLS design development.

A. ACLS in IHI ISPR Accommodation

The ACLS is actually planned to be installed and operated in the Columbus module at COL 1A1 Rack position that is actually occupied by Express Rack ER-3, see Figure 3.

1. *Design Development*

ACLS is accommodated for launch, as a fully integrated (IHI) ISPR rack, see Figure 4, in the pressurized compartment of the Japanese HTV. A reservation in that respect applies to the CCA adsorber beds that may be designed for separate launch to allow for a reduction of its thermal mass and thus steam consumption for CO_2 desorption ,see below for further details.

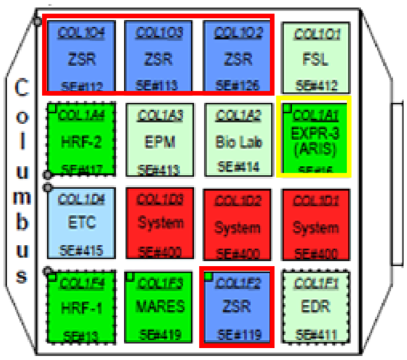


Figure 3. Rack Allocations in Columbus Module

ACLS is designed for in-orbit maintenance thus comprised of exchangeable Intermediate Maintenance Items (IMI) that are compatible with launch on on all available ISS resupply vehicles and that fit through the Russian hatch. Reference is made to Table 1.

Figure 4. ACLS in IHI ISPR Accommodation (w/o closure panels & OGA safety dome)

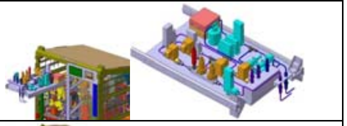
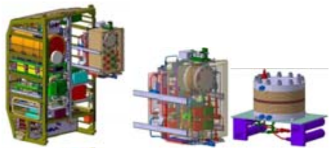
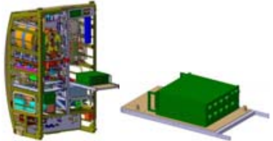
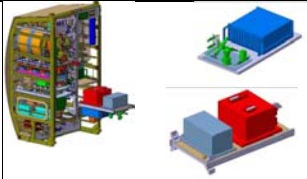
IMI # 1 CCA 3-bed adsorber section	
IMI # 2 CO2 Management	
IMI # 3 CRA mounted to **IMI # 4** CCA Air -& Water management **IMI # 5** OGA assembly **IMI # 6** CCA power supply	  
IMI # 7 ACLS System Controller ASC, OGA Stack Current Source	
MI # 8 AAA Items, WMS Consumable Cartridges	

Table 1. ACLS H/W Breakdown into Intermediate Maintenance Items (IMI's)

The ACLS configuration was further enhanced & validated and further design development was done as follows:

- assessment and revision of ACLS overall schematic in terms with emphasis on simplifications in line with required functionality and safety
- rack allocation of avionics concluded from avionics architecture trade;
- thermal assessment and conclusion on substitution of air cooling via Avionics Air Assembly (AAA) by water cooling and fire detection concept without smoke sensor; Sabatier reactor-2 remains air cooled, see Figure 6 and Figure 11, however, by means of a bypass flow to the CO_2 adsorber's forced air flow.

2. Outlook

The present ACLS configuration will be revisited and further design development will be done addressing aspects such as e.g.

- accommodation of water supply & return interfaces and corresponding ACLS water management equipment;
- thermal analysis and Rack accommodation of water cooling i.e. cold plates & pipes;
- accessibility of Life Limited Items LLI for in-orbit preventive & corrective maintenance;
- testability of zero-g configuration on ground;
- structural analysis of launch configuration;

B. ACLS Subsystems

The ACLS functional block diagram is given on Figure 6. ACLS is subdivided into the following subsystems:

1. Pre-Integrated Rack Assembly (RACK)
2. CO_2 Concentration Assembly (CCA)
3. CO_2 Reprocessing Assembly (CRA)
4. Oxygen Generation Assembly (OGA)
5. Water Management (WM) Subsystem
6. Avionics Subsystem (including Software)

1. Pre-Integrated Rack Assembly (RACK)

The ACLS Pre-Integrated Rack Assembly (RACK) consists of

- the Rack structure itself, i.e. an IHI ISPR standard rack with its secondary structure supporting the mounting of IMI's and supplementary equipment;
- the Air Ducts & Fluid Lines to connect the subsystems and to connect to ISPR UIP interfaces;
- the Harness and
- the Cold Plates and piping for active water cooling of Avionics boxes and condensing heat exchangers.

For design development and outlook reference is made to above chapter A on ACLS in IHI ISPR Accommodation.

2. CO_2 Concentration Assembly (CCA)

In continuous operation ACLS shall remove $\geq$ 3 kg/day CO_2 from the cabin air at a nominal CO_2 level of 4 hPa. Such requirement is satisfied by the CCA subsystem.

The CO_2 loaded cabin air is flowing through the CCA's resin beds filled with Astrine™, which adsorbs the CO_2. By slightly overheated steam supplied by the CCA's Steam Generator the CO_2 is being desorbed, passed through a CO_2 drying stage i.e. Water Recovery Unit and then fed to the CRA. Reference is made to Figure 5.

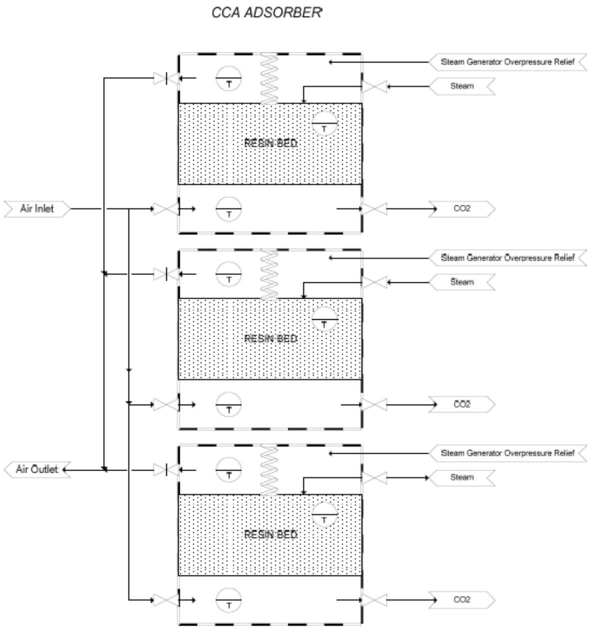


Figure 5. CCA Adsorber Functional Schematic

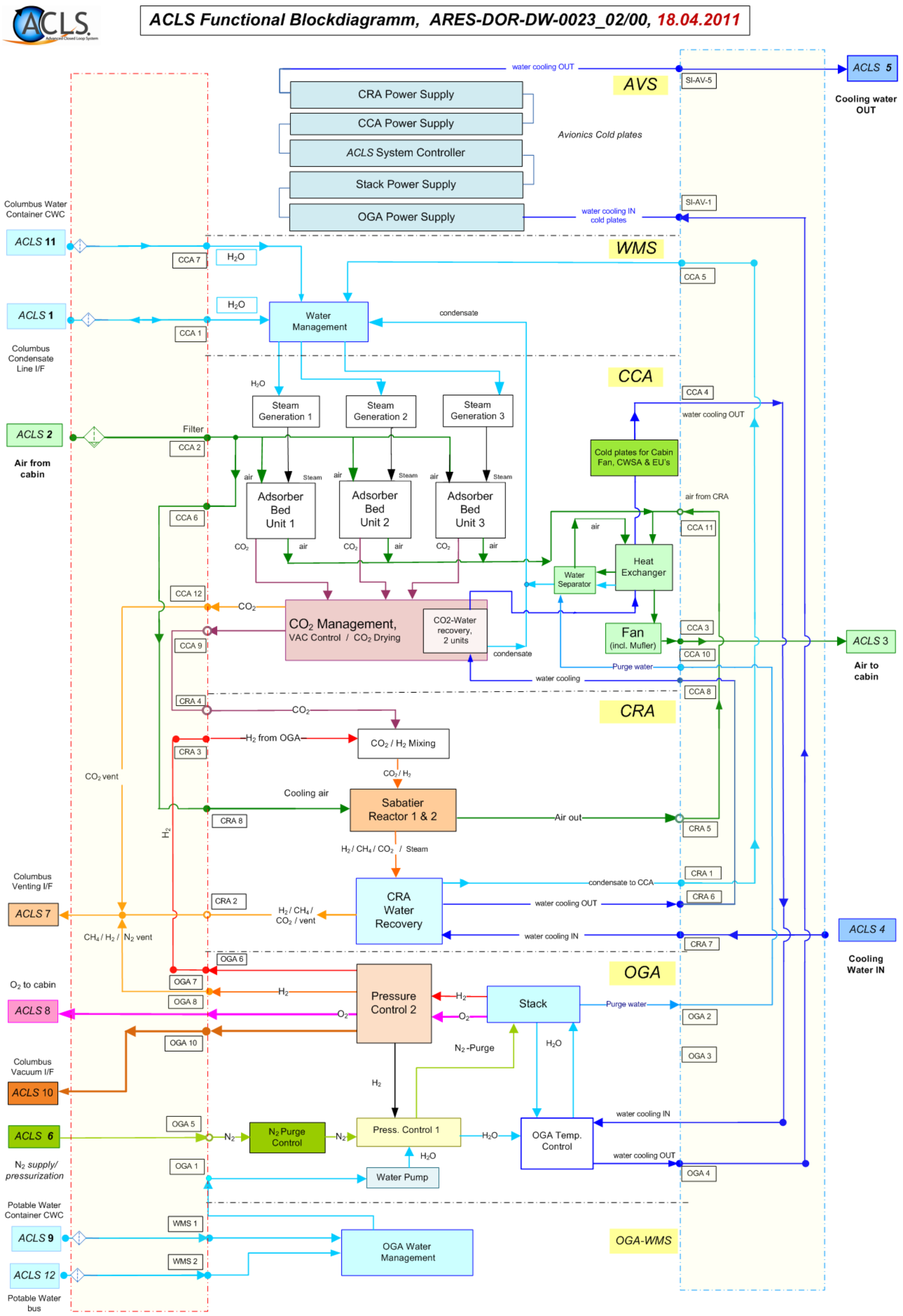


Figure 6. ACLS Functional Block Diagram

2.1 Design Development

The CCA contains three adsorber sections for matching the different adsorbing and desorbing modes to provide continuous CO_2 flow to the CRA assembly for hydrogen conversion to water and methane; see Figure 7 and Figure 8.

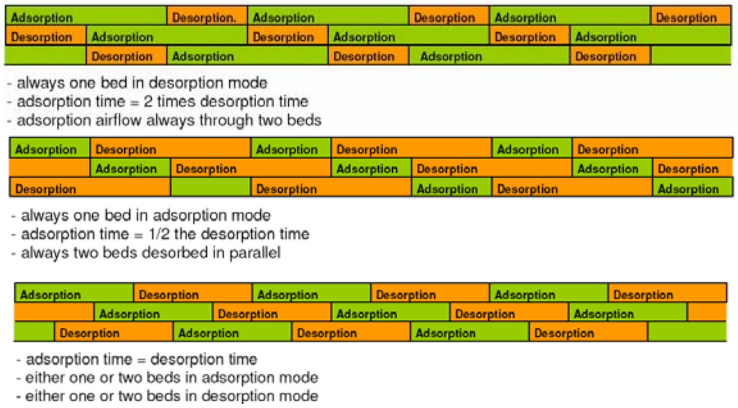


Figure 7. Examples of CCA Operation Sequences

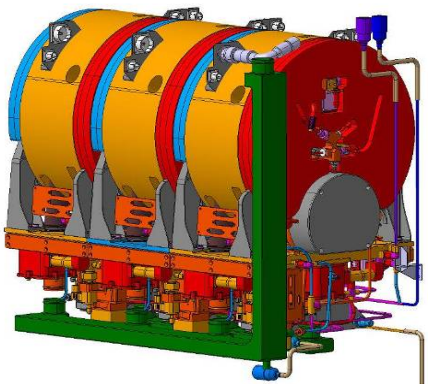


Figure 8. 3-Bed Adsorber Layout

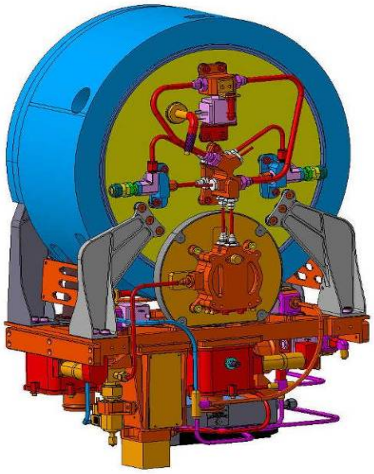


Figure 9. 1-bed Adsorber Section

Each Adsorber Section, see Figure 9, mainly comprises:

- a support structure,
- the Adsorber Bed, including
  - Astrine™ container,
  - a volume expansion mechanism,
  - temperature sensors;
- ducting and mechanisms for the fluid control, namely air inlet and outlet proportional modulating valves and solenoid valves for steam supply and CO_2 release and Steam Generator flow control;
- appropriate thermal insulation and decoupling to minimize heat losses from the resin container and the steam generator during the regeneration phase;
- the steam generator, and
- the CO_2 water recovery heat exchanger.

In adsorption mode the CCA collects carbon dioxide from an airflow by the ion exchange resin Astrine™. Superheated steam is applied during the desorption phase to release again the bound CO_2 from the loaded Astrine™.

Further adsorption / desorption performance testing was done with the Engineering Model of such 1-bed adsorber section. Initial assessments were done on modifications i.e. improvements concluded from test results as follows:

- thermal decoupling of the adsorber container from the base plate
- thermal decoupling of interconnected parts (brackets, air plenums, air valves and incorporation of steam flaps, see Figure 10)
- thermal decoupling of inner internal liner from external liner (avoid thermal bridges)
- minimisation of container bed external surface temperature
- reduction of insulation mass / heat capacity
- limitation of internal sensors and cabling
- minimisation of heat losses, especially heat loss paths via interconnected equipment

Figure 10. CCA Steam Flap

2.2 Outlook

Modifications to be considered for flight configuration development will be analysed further in view of the complete set of applicable requirements. Final proof shall result from performance testing with a next EM 1-bed adsorber that shall fully comply - wrt form, fit, function, with such flight configuration.

3. CO_2 Reprocessing Assembly (CRA)

In continuous operation ACLS shall generate at least 1.2 kg/day of liquid water from the reaction of Hydrogen and CO_2. Such requirement is satisfied by the CRA Subsystem.

The CRA Sabatier reactor receives the CO_2 directly from the CCA. Upstream of the reactors it is mixed with the hydrogen from the OGA, see Figure 11.

Downstream of the Sabatier reactors a water recovery unit cools the hot product gases consisting of methane, water vapour and excess CO_2 down. The condensate is routed to the water management subsystem for reuse. The product gases then flow to the vacuum control section and then to the vent line.

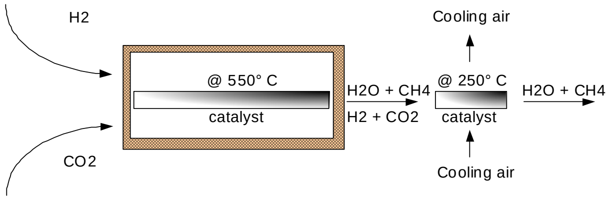


Figure 11. Sabatier principle with two reactor stages

3.1 Design Development

The actual design layout is given on Figure 13. An Elegant Breadboard - with EM like Sabatier reactor - was built and tested successfully in course of ACLS phase B; reference is made to the hardware picture given on Figure 12. Recent development activities did concentrate on the preliminary design of a 3-crew section is support of upcoming EM reactor section procurement.

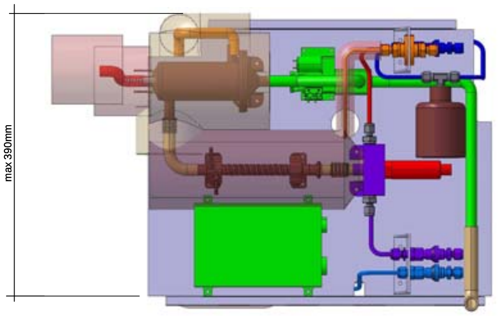


Figure 13. CRA (View of Reactor Side)

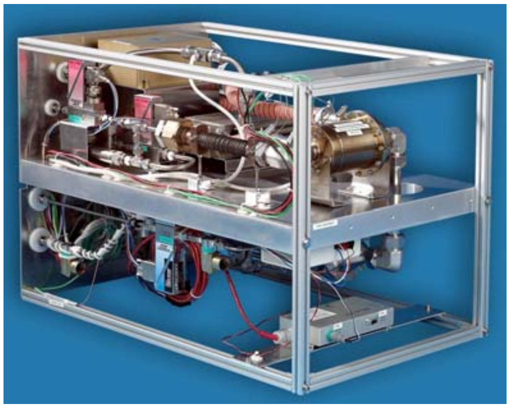


Figure 12: CRA Elegant Breadboard

3.2 Outlook

An Engineering Model of the reactor section downscaled to 3-crew application shall be manufactured and tested, mainly wrt performance and wrt compliance with mechanical loads.

4. Oxygen Generation Assembly (OGA)

In continuous operation ACLS shall generate at least 2.52 kg/day O_2 by electrolysis of water. Such requirement is satisfied by the OGA Subsystem. For electrolysis principle reference is made to Figure 14.

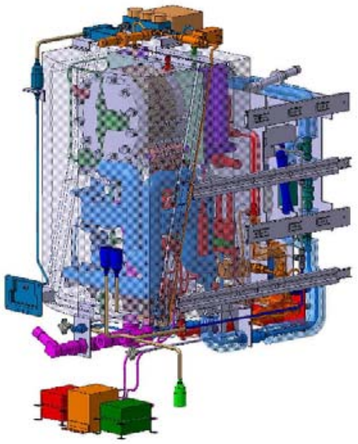


Figure 15. OGA layout, Dome with implemented stack and water loop on the back side

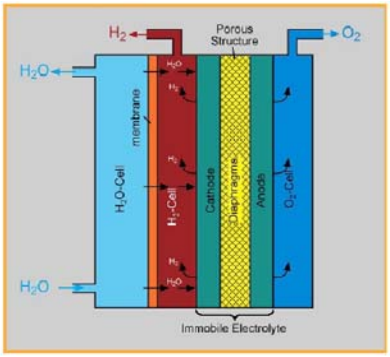


Figure 14. OGA Electrolysis Principle

The oxygen produced by the OGA is released to the cabin while the hydrogen is routed to the CRA. All components which contain hydrogen at pressures above ambient are housed in a safety dome. Further reference is made to Figure 15 for OGA IMI layout.

4.1 Design Development

Emphasis was put on below identified design aspects that were addressed and further clarified as follows:

- OGA stack component detailed design development and validation through testing (perforated disc, membrane, seals) with the latest stack assembly configuration having achieved > 7.800 hrs lifetime through testing;
- power loss / ventline loss testing; from testing it is concluded that a degradation of the FAE - visible through impedance measurement - may start about 15 minutes after shutdown if the water compartment has not been purged.
- FAE electrolyte (KOH) adsorption & contamination by CO_2 respectively alcohol in the process water; from testing it is concluded
  - what CO_2 content is affordable i.e. what limit is to be ensured by the water treatment unit, and
  - that alcohol shall be excluded i.e. that condensate may not serve as source for OGA water supply

4.2 Outlook

Near term breadboard activities related to the OGA will emphasise on

- continuation of stack lifetime testing;
- testing on suitability of impedance measurement to serve as FAE process control parameter, in support of a final disposition to consider such functionality in the ACLS avionics architecture.

5. Water Management Subsystem (WMS)

ACLS requires water

- for water electrolysis in the OGA, and
- for steam desorption in the CCA.

A built-in Water Management Subsystem shall handle all internal and external water sources of the ACLS system and shall provide the water quality as needed for the ACLS assemblies CCA and OGA or in case of water surplus inside ACLS the supply back to the station interface.

ACLS recovers internally condensate from the product gases at different locations; the condensate needs to be treated / decontaminated and conditioned by the ACLS water management before its re-use inside ACLS. In addition external water sources are considered as follows:

- use of COLUMBUS water condensate line for water supply to CCA;
- condensate supply to CCA via external water bag CWC;
- potable water supply to OGA via external water bag CWC-I.

A further option being considered is the water supply to the OGA via dedicated potable water line, using the fuel cell water bus available in Node2.

Reference on subject is made to below Figure 16.

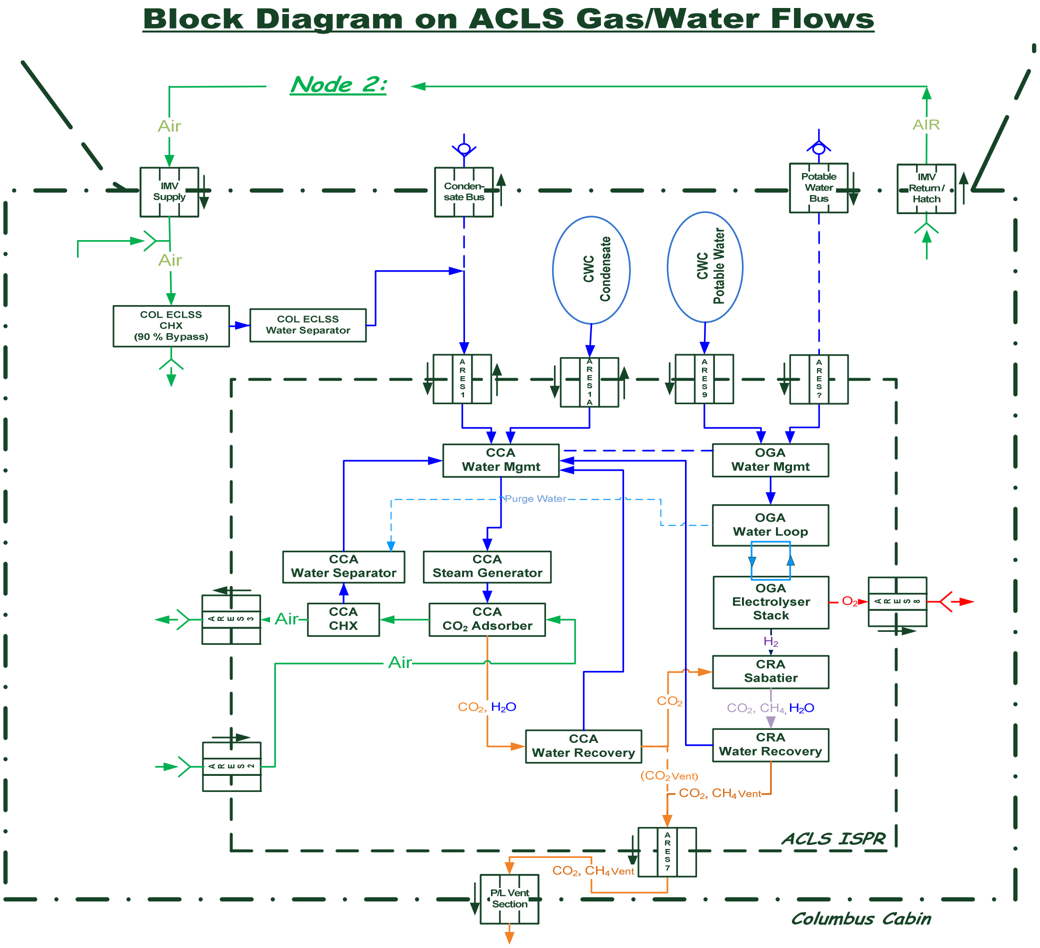


Figure 16. ACLS Gas / Water Flows

5.1 Design Development

Recent development activities did further concentrate on the analysis of requirements to be applied on the WMS i.e. on the determination of water qualities required by the equipment supplied with water by the WMS being the OGA electrolyser and the CCA Steam Generator. In terms of OGA referenced is made to the contamination test activities outlined in above chapter 4.

Concluded from the above an initial trade-off was done on suitable water treatment & quality monitoring technologies.

5.2 Outlook

Near term activities will emphasise on

- the further assessment of the process water balance in support of trade-off & final disposition on water supply alternatives;
- the development and testing of advanced breadboards of the units for water treatment and water quality monitoring wrt both, potable water supply to OGA and condensate supply to the CCA.

6. Avionics Subsystem (including Software)

The ACLS avionics subsystem will control the ACLS CCA, CRA and OGA processes and provide them with the necessary electrical power. In addition it includes the system element interfaces for data handling and power supply.

6.1 Design Development

The avionics hardware block diagram is comprised on Figure 17, reflecting an avionics configuration as concluded from the latest architecture trade.

6.2 Outlook

The avionics architecture definition will be further advanced in reply to the baselining of functionalities and interfaces resulting from system design development. Based on user requirements definition the software development will be initiated.

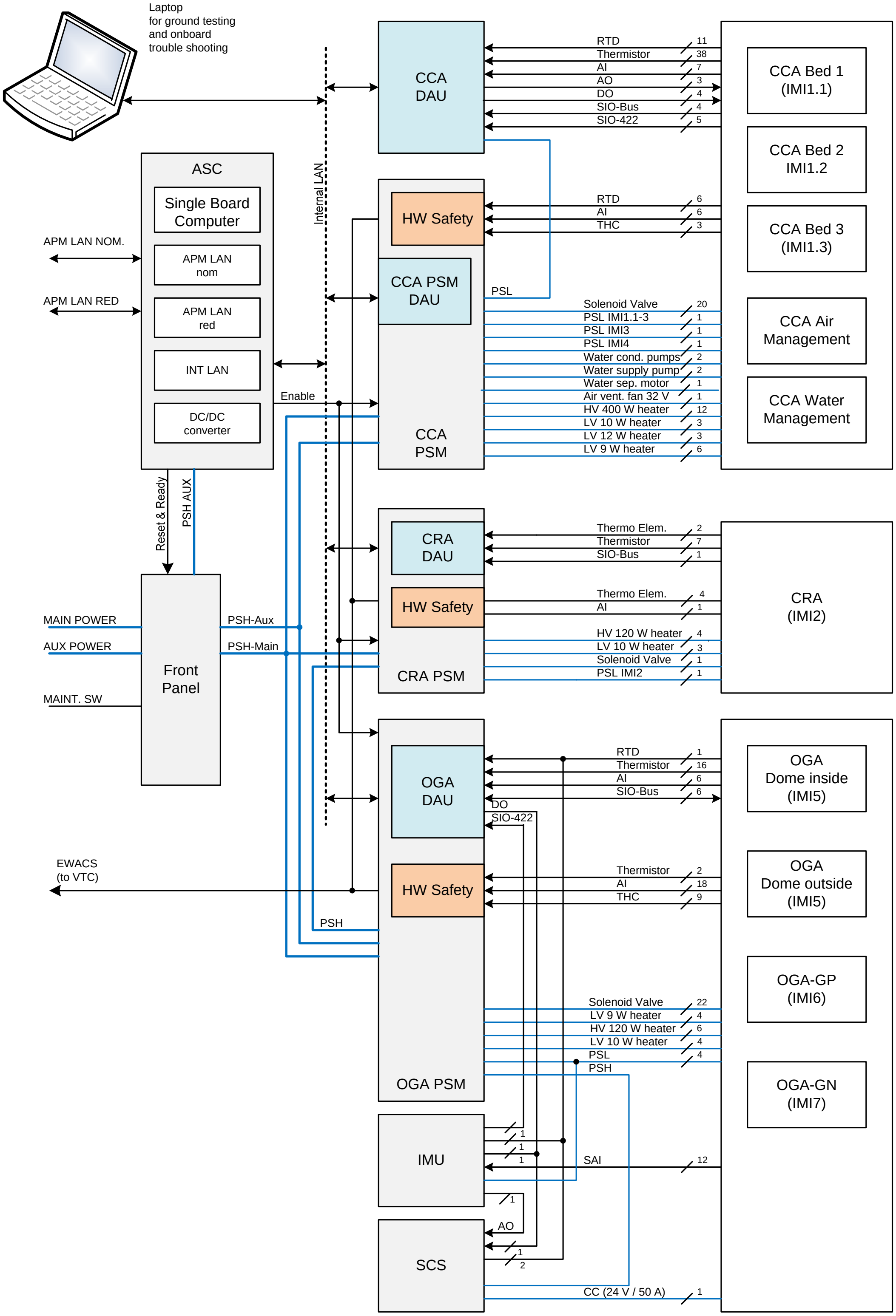


Figure 17. Avionics H/W Block Diagram

III. Programmatic

ACLS system level activities subject to present phase C1 will be completed in May 2011. On component level the development and EM manufacture of CAM/COTS items for electrolysers & fuel cells is in process. Items under development are pressure sensors, gas sensors and a KOH filter, all of them well suited for application in ACLS. In addition, subject to ESA's Aurora programme, the further development of the ACLS' CRA reactor section, the CCA cabin air supply fan & muffler, the Ventline Pressure Control Section and the WMS are being initiated these days. Furthermore, the development of the electrolyser is continued, subject to German national funding, for its application in both, regenerative fuel cell systems for exploration missions and in life support systems such as ACLS.

In March 2011 the ESA Council granted the financial support to the extension of European participation in the ISS Expoitation until 2020. Amongst others, the council's resolution allows for enhancements being initiated as Industry investments, with a Return of Investment through ESA's payment for services. A major element considered is the ACLS which, being operable on the ISS from 2016 onwards, will serve - as a supplement to the International partners' systems - for oxygen supply, CO2 removal and reprocessing i.e. loop closure through the production of water. In view of above perspective full phase C/D authorisation is envisaged for autumn 2011.

IV. Conclusion

Significant progress has been made throughout the present ACLS Phase C1. The achieved design maturity level provides a solid basis for the envisaged ACLS phase C/D up to the installation and operation of ACLS on the ISS as part of a thus enhanced ISS life support system.

Acknowledgments

The work has been performed under contract of the European Space Agency (ESA).

References

[1] Funke, H.; Bockstahler, K.; Raatschen, W.; Witt, J,; Hovland, S., *Design Status of the Closed-Loop Air Revitalization System ACLS for Accommodation on the ISS,* 37th International Conference on Environmental Systems (ICES), Paper 2008-01-2189, San Francisco, June 29 - July 02, 2008

[2] Funke, H.; Bockstahler, K.; Raatschen, W.; Witt, J,; Hovland, S., *Design Status of the Closed-Loop Air Revitalization System ACLS for Accommodation on the ISS,* 38th International Conference on Environmental Systems (ICES), Paper 2009-01-2506, Savannah, July 12 - 16, 2009

[3] Bockstahler, K.; Funke, H.; Brodt, K.; Witt, J, *Design Status of the Closed-Loop Air Revitalization System ACLS for Accommodation on the ISS,* 39th International Conference on Environmental Systems (ICES), Paper ID 760857, Barcelona, July 12 - 15, 2010

[4] Bockstahler, K.; Schaefer, Lucas, J.; Raatschen, W., *Methane Pyrolysis Technology as Part of Life Support and ISRU Systems,* 37th International Conference on Environmental Systems (ICES), Paper 2008-01-2190, San Francisco, June 29 - July 02, 2008

[5] Williams, David E., *International Space Station Environmental Control and Life Support System Changes for Increasing the ISS Crew Size to Six Crew Members and for Shuttle Retirement,* 37th International Conference on Environmental Systems (ICES), Paper 2008-01-2178, San Francisco, June 29 - July 02, 2008