MARKET OPPORTUNITIES FOR ADVANCED VENTILATION TECHNOLOGY

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Title: Ventilation and Air Revitalization on the International Space Station (ISS)

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Abstract: The International Space Station (ISS) is the biggest multinational space program ever with 16 countries involved. Since November 2000 the station is permanently occupied with a crew of 3 astronauts. Till 2006 the station will be further assembled and the crew will be increased to 7 astronauts. To maintain a comfortable and safe environment under micro gravity conditions in a completely sealed space habitat advanced ventilation technology had to be developed to maintain air temperature, air humidity and air velocity as well as contaminant concentrations well below required levels. As resources are limited and upload costs are extremely high, one focus within the space station program is to close the oxygen loop, i.e. to recycle the exhaled CO_2 laden air into fresh air.

The paper gives a brief overview about the overall ventilation and contaminant removal system on the ISS and focuses on developed equipment and performance of closed loop system devices. Technology transfer examples of space hardware for terrestrial application within the HVAC community is given and market opportunities are shown.

1 INTRODUCTION

The ISS is a global partnership of 16 nations representing six space agencies, including the United States National Aeronautics and Space Administration (NASA), Russian Space Agency (RSA), European Space Agency (ESA), Japanese National Space Development

Agency (NASDA) Canadian Space Agency (CSA), and Italian Space Agency (ASI). The participating countries are Belgium, Brazil, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Norway, Russia, Spain, Sweden, Switzerland, the United States, and the United Kingdom. The ISS operates at an altitude of approximately 310 to 350 km (170 to 190 nautical miles) and an inclination of 51.6° to the equator.

The International Space Station Program is divided into three phases. Phase 1, completed in 1998, consisted of the joint Shuttle-Mir missions to prepare for the ISS build phases. Phase 2, the initial ISS construction phase, began assembly in November 1998, established permanent crew operations in November 2000, and has culminated with the Airlock flight in July 2001. A total of 13 ISS flights have been completed, including 10 Shuttle flights. Phase 3 will complete the ISS assembly, culminating with seven-person permanent presence supported by combined Russian and U.S. life support capabilities and six on-orbit Laboratories. At its completion, the ISS is planned to be approximately 108,5 m wide x 88.4 m long x 43.6 m high. It will have an on-orbit mass of approximately 450,000 kg and have an internal pressurized volume of approximately 1,220m^3:

Figure 1 shows a flight photo after the ISS-Flight 7A assembly in July 2001 and Figure 2 displays a three dimensional view of the ISS at Assembly complete

Figure 1: ISS Flight 5A Configuration, July 2001

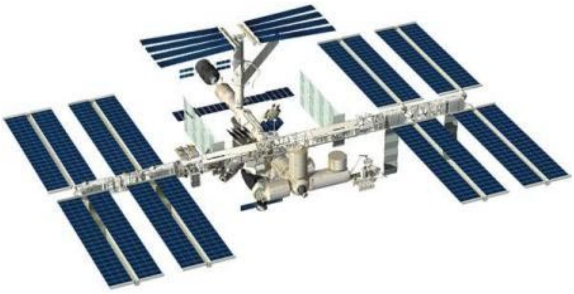

Figure 2: ISS Assembly Complete Configuration

The ISS Environmental Control and Life Support (ECLS) provides the basic life support functions to support the crew, while maintaining a safe and habitable shirtsleeve environment. The ECLS hardware providing this functionality is organized into seven subsystems: Atmosphere Revitalization (AR), Temperature and Humidity Control (THC), Fire Detection and Suppression (FDS), Atmosphere Control and Supply (ACS), Water Recovery and Management (WRM), Waste Management (WM), and Vacuum System (VS). The principal ECLS hardware distribution across ISS elements is shown in Figure 3. The ECLS functions for the first two subsystems, where the description of this paper is limited to, are listed below:

Temperature and Humidity Control:

- Cabin air temperature and humidity control
- Equipment air-cooling
- Inter- and intra-module ventilation for crew comfort and station level control of CO_2, O_2, and trace contaminants

Atmosphere Revitalization:

- Control and disposal of carbon dioxide (CO_2)
- Control of airborne trace contaminants
- Oxygen (O_2) supply via generation
- Atmosphere monitoring of primary constituents, including CO_2, O_2, nitrogen (N_2), hydrogen (H_2), methane (CH_4), and water vapor
- Airborne particulate and microbial control

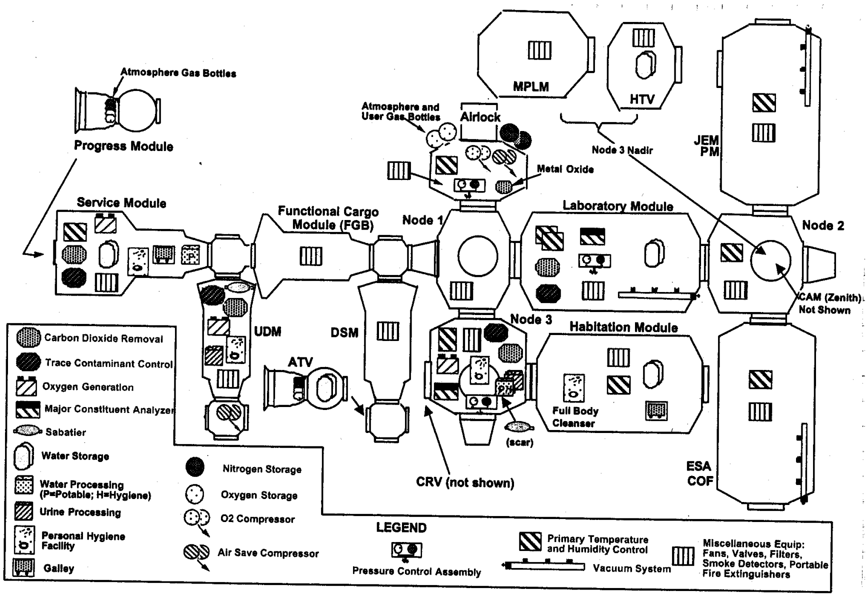

Figure 3*:* Principle ECLS Hardware Distribution Across ISS Elements (acc. to /1/)

This paper is limited to describe temperature and humidity control and atmosphere revitalization.

2 TEMPERATURE AND HUMIDITY CONTROL (THC)

Except the airlock, where the total pressure can be reduced, the atmosphere in the ISS is comparable to the earth environment, 1bar total pressure, 21 vol %. O_2, 79 vol % N_2.

Total air flow rate	420 m^3/h to 460 m^3/h
Sensible heat load	200 W to 2500 W
Latent heat load	0 W to 300 W
Cabin air temperature range	18 to 27
Cabin air relative humidity	25% to 70%
Water carry-over in air flow	< 2% of condensed water
Coolant water temperature	5°C ± 1°C
Coolant flow rate	128 kg/h to 617 kg/h

Table 1: TH C system requirements

The THC subsystem ensures that the temperature and humidity levels in the atmosphere are within the design specifications. Heat enters the atmosphere from the crew (metabolically generated heat) and equipment (lights, etc., although, much of the equipment—generated heat is removed by cold-plates). Humidity enters the atmosphere primarily from crew respiration and perspiration. The Common Cabin Air Assembly provides adequate ventilation, and temperature and humidity control for the cabin. For COLUMBUS (see ESA/COF module in Figure 3), the European contribution to the ISS program, the requirements for the THC are listed in Table 1:

2.1 The Condensating Heat Exchanger

Temperature and Humidity control is achieved by a condensating heat exchanger (CHX). The schematic of the COLUMBUS THC subsystem /2/ is shown in Figure 4.

The warm and humid air stream from the cabin is divided by the temperature control valve (TCV). One part of the air flow passes through the active (i.e. cooled) CHX core and the other part through the inactive (i.e. not cooled) CHX core which acts as a bypass. The TCV position is controlled by the cabin temperature control unit, and so the cabin air temperature is maintained at the desired value.

The air flowing through the active core is cooled down close to coolant water temperature. Consequently part of the humidity contained in the air flow is condensed. The condensate is transported by the air drag to the condensate removal section at the end of the CHX core. Here the condensate water separator assembly (CWSA) sucks a certain amount of air which takes the condensate with it. In the CWSA the condensate is separated from the air and fed into the condensate system of the ISS, whereas the air is fed back to the main air stream to the cabin.

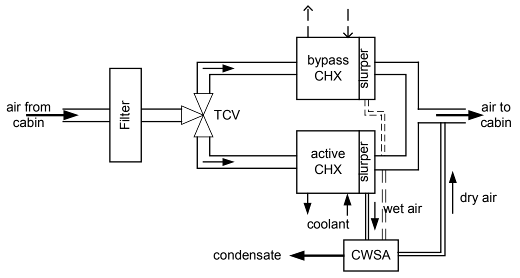

Figure 4: Schematic of the COLUMBUS THC subsystem.

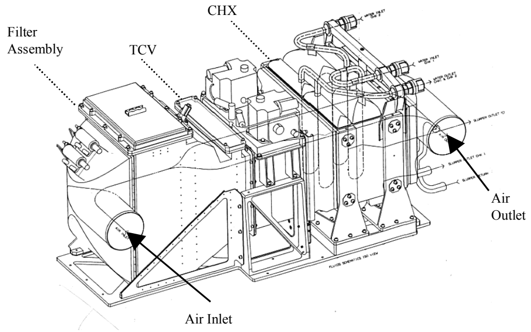

Figure 5: Condensing Heat Exchanger Fan Assembly (CHXFA)

The heat exchanger cores are a brazed plate and fin design which combine compactness and mechanical robustness. The heat exchanger core is a crossflow/cross-counterflow design, with air flow at 90 degrees to water flow.

Under 1 g conditions the condensate in a CHX is pulled down to the bottom of the CHX where it is collected and removed. On orbit, however, the lack of gravity has to be compensated by according design features which ensure the condensate separation: the air flow passages must be coated with a hydrophilic coating which for long missions must be antimicrobial, and a slurper section must be added for water removal.

The hydrophilic coating on the air flow passages of the condensing heat exchanger facilitates condensate film formation. In the operating heat exchanger, the condensate film is moved by the air flow to the slurper section. The slurper section is essentially an extension of the tube sheet with holes in it at the air outlet end, Figure 6. A small negative differential pressure is drawn through these holes such that the condensate is pulled through them, thus achieving efficient air/condensate separation.

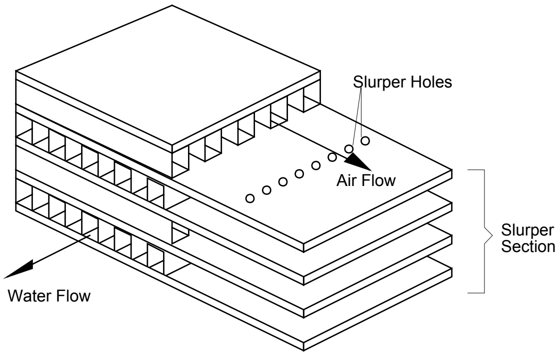

Figure 6: Slurper design principle

Air flow rate	12 kg/h to 28 kg/h
Air pressure rise	600 Pa at 20 kg/h
Condensate flow rate	1.2 kg/h
Condensate slug capacity	50 ml per 20 sec.
Power consumption	40 W

Table 2: CWSA performance data

2.2 Condensate Water Separator Assembly

The CWSA sucks air with entrained water droplets from the slurper of the CHX core. A centrifuge separates the condensate droplets from the air, transports the water back to the water recovery system and feeds the air back into the air ductwork.

2.3 Ventilation

According to /3/ there are four main tasks from the ventilation system in the COLUMBUS cabin to be fulfilled:

- Achievement of an almost uniform air velocity within the habitable volume of the cabin which is high enough to enable convective heat transfer from the crew body surface to the air and which is low enough to avoid thermal discomfort
- Supply of necessary amount of fresh air to all locations within the habitable volume
- Removal of generated contaminants in the cabin by dilution
- Provision of fast fire detection through all operational phases in case of emergencies.

The velocity requirement for the Columbus cabin is given in Table 3. The cabin consists of a habitable volume of approx. 20 m^3 and the hatch related volume of 5 m^3. The high quality of the velocity distribution is a prerequisite for an indoor climate acceptable by the astronauts.

Ventilation System Design

The air flow is driven via eight cabin air diffusers into the cabin. The cabin flow field which is mainly influenced by the cabin air diffuser nozzle adjustment (for air diffuser see Figure 7) has been optimized. On one hand it is important to achieve a homogenous air flow pattern in the cabin on the other hand the crew shall not be impacted by jets coming from the cabin air diffuser outlet.

In the vicinity of the diffuser outlet the fresh air injected via the cabin air diffusers (primary air) induces a significant amount of cabin air (secondary air). The main primary air paths are driven along the cabin ceiling and lateral walls. The optimization task was to adjust the primary air jets direction in the way to reduce air friction loss along the walls and also to avoid over speed areas in the habitable volume. Driving the primary cabin air mainly along the cabin walls, the impact on the crew caused by a temperature change is minimized.

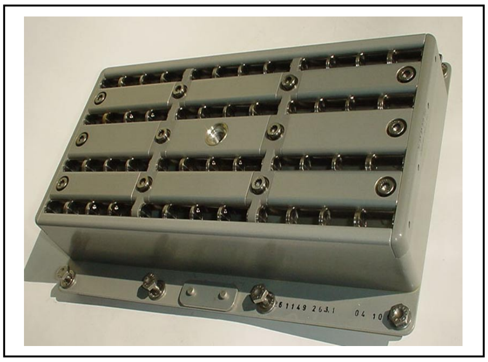

Figure 7: Air Diffusor in COLUMBUS

Velocity Range	Requirement	Result
0.076 to 0.203m/s (15 to 40 feet/min)	67% of all measured air velocities shall meet this range	80.5 % of all measured air velocities meet this range
0.036 to 1.016m/s (7 to 200 feet/min)	All measured air velocities shall meet this range	Lowest value: 0.043m/s Highest value: 0.476m/s

Table 3: Test Results vs. Requirements for the Habitable Volume in COLUMBUS

3 ATMOSPHERE REVITALIZATION

3.1 Control and disposal of carbon dioxide (CO_2)

As can be seen from Figure 3, there is one CO_2 removal assy in the US Laboratory Module, one is foreseen in the US-Node 3, and one is operating in the Russian Service Module. All three use molecular sieve technology. The CO_2 laden air, which is sucked through one bed of the CO_2 removal assy, adsorbs the CO_2 molecules. After saturation the cabin air is passed through a second bed for further adsorption. During this cycle bed 1 is desorbed by applying space vacuum thus venting the CO_2 into space. If all three systems fail, LiOH-cartridges are on board to scrub CO_2 for a contingency period of 45 days.

The CO_2 concentration is monitored in each module. The reading leads to adequate means if the CO_2 concentration is out of the nominal range (7,030 – 10,130 ppm).

Intermodular ventilation among the various modules is high enough, see Figure 8, to ensure no exceeding of maximum CO_2 level independent of how the crew is distributed among the modules.

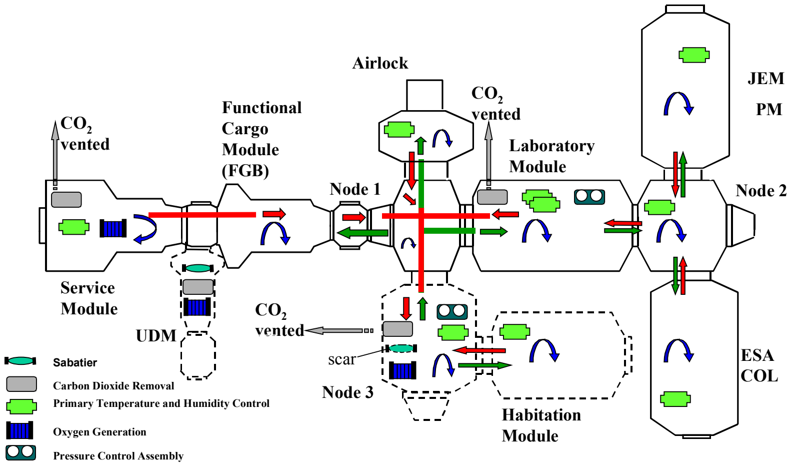

Figure 8: Air distribution on ISS

3.2 Control of air borne trace contaminants

Atmospheric trace gas contaminants that are generated during normal operations are maintained at levels below the 180-day SMAC levels and the removed gases are disposed of.

3.3 Oxygen (O_2) supply via generation

The oxygen concentration is monitored over a range of 0 to 40.0 kPa with an accuracy of ± 2% of full scale in each module, either by a O_2-sensor or via the Major Constituent Analyzer. The O_2-level is kept to 19.5 to 23.1 kPa.

The day by day O_2 production is by means of water electrolysis. One electrolyzer is foreseen in the US-NODE 3, while the second one is already operating in the Russian Service Module. Backup systems are Solid Fuel Oxygen Generators, which are of similar technology as the emergency oxygen generators in most passenger airplanes and gaseous oxygen supply from the two pressurized O_2-tanks.

3.4 Atmosphere Monitoring

The presence and concentrations of atmospheric contaminants are monitored and excess contaminants are removed from the habitat atmosphere.

Major constituents are continuously monitored in the ISS atmosphere, including the European, Japanese, Italian and U.S. modules /4/. The Sample Delivery Subsystem provides the sample ports at the desired sampling locations. Samples are collected in sequence from the different ports once each minute and are analyzed for O_2, N_2, CO_2, H_2, CH_4 and H_2O. The capability for rapid sampling is also available (every 2 sec. from a single port). The information on the atmospheric composition is used to monitor or operate the Atmosphere Control and Supply, the CO_2 Removal System and the Trace Contaminant Control System.

3.5 Control Airborne Particulate Contaminants

Airborne particulate are removed so as to have no more than 0.05 mg/m^3 (100.000 particles per ft^3) with peak concentrations less than 1.0 mg/m^3 (2 million particles ft^3) for particles from 0.5 to 100 microns in diameter.

3.6 Control Airborne Microbial Growth

The daily average concentration of airborne microorganisms is limited to less than 1,000 CFU/m^3. The atmosphere is monitored for bacteria, yeast, and molds, with a sampling volume from 1 to 1,000 L of atmosphere. On surfaces (the source of airborne microorganisms) the acceptable ranges of bacteria and fungi are 0 to 40 CFU/cm^2 and 0 to 4 CFU/cm^2, respectively. Samples are collected once per month and analyzed on earth.

4 CLOSED LOOP AIR REVITALIZATION

Assuming an average activity one person needs 0,85 kg$_{O2}$/day or 325 kg$_{O2}$/year. For the total crew of 7 person on the ISS 2,146 kg of oxygen is needed per year. The major part (1,919 kg) is generated via electrolysis. There is an amount of 684 kg of fuel cell water from the Shuttle transferred during its five 8-day dockings to the station per year. The remaining 1,475 kg of water have to be uploaded. Figure 9 shows the baseline design of the current open oxygen loop system.

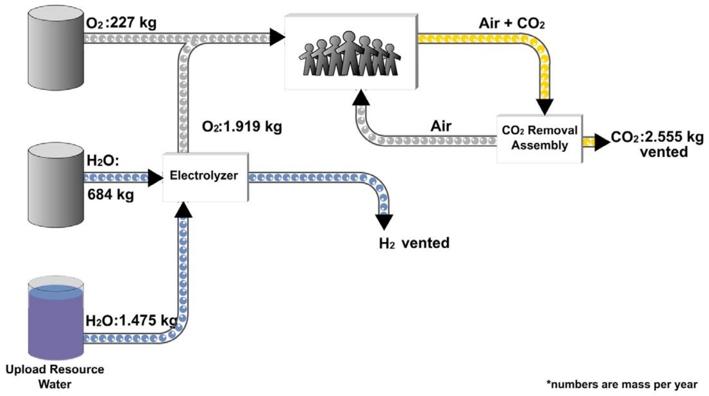

Figure 9: Current state of atmosphere revitalization on the ISS

The seven person crew exhale more than 2,5 tons of CO_2 per year during their stay. This significant mass is vented into space and therefore lost. Astrium's closed loop air revitalization system ARES is shown in Figure 10. Figure 11 shows a test rack with ARES.

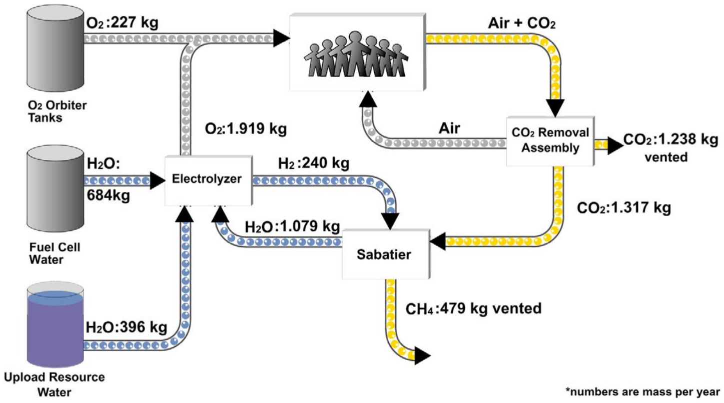

Figure 10: Astrium's closed loop air revitalization tem ARES

Figure 11: Closed Loop Air sys- Revitalization System Demonstrator

4.1.1 The electrolyzer

The electrolyzer splits liquid water into gaseous oxygen and gaseous hydrogen with the aid of electric power. The oxygen is directly mixed with the cabin air. The hydrogen is supplied to the Sabatier reactor.

4.1.2 The CO2 Removal Assembly

The carbon dioxide in the cabin air is absorbed by means of two absorber/desorber beds consisting of a specially activated ion exchange rasin. Desorption is carried out with the aid of water vapor at temperatures just above 100°C. One half of the desorbed CO_2 is transferred to the Sabatier reactor together with hydrogen from the electrolyzer.

4.1.3 The Sabatier Reactor

The Sabatier reactor is a catalytic reactor made of noble metal on ceramics which – once it has been heated – reduces the CO_2 and the hydrogen to methane and water vapor without energy supply at temperatures of about 600°C. While methane is currently not used on the ISS and therefore vented to space, the recovered water is extremely valuable. It is supplied to the electrolyzer and the oxygen cycle is thus closed.

ARES reclaims approx. 1,000 kg of water annually which is equivalent to 30 Mio US$ upload cost savings per year.

5 SPIN-OFFS

5.1 Air revitalization system, ARES

There are needs on earth to live in completely sealed compartments, like

5.1.1 Submarines

Non-unclear submarines usually have diving times of some weeks. There the provision of oxygen supply is done by using pressurized oxygen tanks, as water electrolysis consumes a lot of power. But there is the need for a regenerative CO_2 removal system, as it is installed in ARES. It takes up minimum space, a small amount of energy (3,5 Wh/l_{CO2}) and requires minimum maintenance over its life time of more than 10 years.

5.1.2 Shelters

If there is the need for a really completely sealed compartment (Safe Haven) and electrical power is available, ARES is able to support life w.r.t. breathable air for infinite time.

5.2 Regenerative CO_2 Removal System

5.2.1 Chemical agent protection in Safe Havens and (NBC-) Shelters

NBC-shelters are usually pressurized buildings, where the supply air is purified by active charcoal filters. The pressurization makes sure that no inleakage of chemical/biological agents can occur.

If infiltration passages of air of such a building are known, e.g. a shelter in a mountain or a mine having only a few entrances/exits, the ventilation design as shown in Figure 12 and 13 has some advantages in comparison to a conventional design.

Prior to the Protected Zone a Buffer Zone is foreseen. As also some inleakage from outside is possible, there is a small NBC-filter recirculation system installed in the buffer zone. Compared to the large NBC-filter beds in conventional NBC-shelters to clean the total amount of supply air the buffer zone filter design is very small only for the removal of infiltrated agent into the buffer zone.

- **Open loop design**

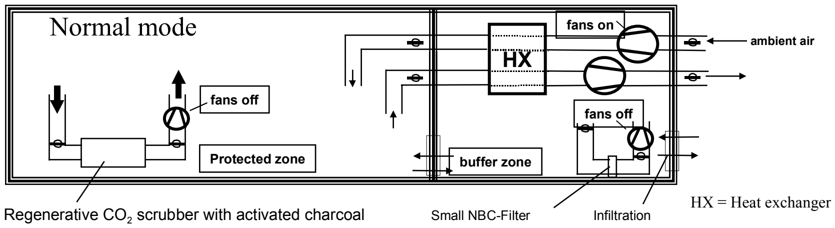

Figure 12: Open loop shelter design

- **Closed loop design**

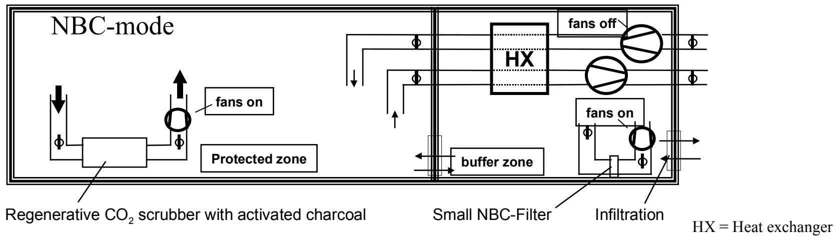

Figure 13: Closed loop shelter design

The protected zone contains a regenerative CO_2 removal system with active charcoal capability to remove metabolically exhaled CO_2 and odors as well.

During Normal-Mode operation a conventional HVAC system supplies outdoor air to the Protected Zone, the CO_2 removal system is off as well as the NBC-filter unit in the buffer zone.

In case of an attack, with or without sensors to control the system, the HVAC system is turned off and sealed dampers take care that no outdoor air enters the protected zone via HVAC ductwork. The NBC-filter unit is turned on to remove infiltrated agents into the buffer zone. The CO_2 removal system is turned on to keep the CO_2 concentration on the required level. Advantages of such a shelter design are

- No time consuming NBC-filter activation when switching from Normal to NBC-Mode
- Lower invest and operations cost for NBC-filter as only infiltrated air has to be cleaned, but investment for CO_2 removal system is needed
- Limited maintenance, life time > 10 years
- With agent detection devices, also protection against sudden chemical attacks is given due to immediate switch from Normal to NBC–Mode
- NBC-Mode possible also under normal conditions to save energy for makeup air

The O_2 supply options depend on the designed protection duration

- No O_2-supply necessary (short protection, hours)
- O_2-supply via gas bottles (medium protection, days)
- O_2 generation via electrolysis (long protection, weeks)
- O_2 supply via ARES (unlimited protection, only power required)

5.3 Decentralized CO_2 Removal System

The decentralized CO_2 removal system in Figure 14 is suited for rooms where air supply is not wanted (e.g. cashier rooms) or rooms with too low air supply rates. The CO_2 removal unit could be a stand-alone device or can be integrated into a cabinet. CO_2 desorption can be accomplished with steam or warm air. The desorbed CO_2 is either vented into an exhaust duct or directly to the outside.

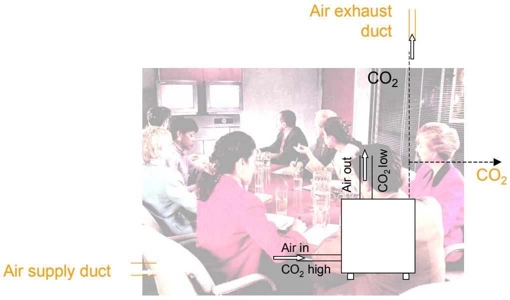

Figure 14: Decentralized CO2 scrubber for e.g. a meeting room

Figure 15: CO2 removal system in a fruit store with controlled atmosphere

5.4 Fruit Storage under Controlled Atmosphere

Fruit preservation is accomplished by storing fruit in a controlled atmosphere. The fermentation process is slowed down at partial pressures of 1 vol% $< p_{O2} <$ 3 vol%; 1 vol% $< p_{CO2} <$ 3 vol.%. The fruit takes up O_2 and produces CO_2. Both gases have to be controlled. Especially for mobile fruit containers, where a small volume of a CO_2 removal system is favorable, the Astrium CO_2 removal system has advantages compared to common soda lime systems:

- Low CO_2 partial pressure (< 0,5 Vol.%) inside the storage room
- Low O_2 contamination of the storage room by desorption with air
- Zero O_2 contamination of the storage room by desorption with water steam
- Low installation mass for the adsorber bed
- Low installation volume for the adsorber bed

6 CONCLUSIONS

The ventilation and air revitalization system of the International Space Station has been explaned. The currently baselined open loop for the regeneration of metabolically produced CO_2 into breathable oxygen was outlined and the technical realization of a closed loop system with its benefits to the ISS program was detailed.

Up til now limited spin-off ideas have been generated so far for a closed loop air revitalization system for terrestrial applications.

However, the CO_2 removal system shows promising perspectives for future applications in the HVAC industry.

7 REFERENCES

/1/ James L. Reuter, Richard Reysa: International Space Station Environmental Control And Life Support System Status: 2000-2001, Proc. of 31st International Conference on Environmental Systems, July 9-12, 2001Orlando, Florida, paper 2001-01-2386

/2/ L. Eicher, G. Hauser, R. Mueller, S. Rose, H. Fourquet, T. Morel: System Aspects for Humidity Removal under Zero Gravity, Proc. of 30th International Conference on Environmental Systems, paper 2000-01-2312, July 10-13, 2000, Toulouse, France

/3/ T. Haidl, B. Lehr and W. Raatschen: Thermal Comfort, Ventilation Efficiency, Contaminant Removal, Proc. of 30th International Conference on Environmental Systems, paper 2000-01-2298, July 10-13, 2000, Toulouse, France

/4/ Wieland, P. O.: Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station, NASA-MSFC January 1998, NASA/TM-1998-206956/VOL1