A closer look at the ELSS of the Stratospheric Airbus Perlan II.

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The Perlan II is a closed-loop, pressurized, stratospheric engine-less glider. The Environmental Control and Life Support System (ECLSS) is based on a re-breather, closed-loop system. The combination of gases, different pressures and oxygen contents between the cabin and the outside air and the oxygen inside the mask-rebreather makes for a new and interesting approach to solve the ECLSS on a vehicle without external or internal self-produced power while reaching designed altitudes of (Approx. 27.7 KM, 90,000 feet).

The Perlan II achieves a different pressure and oxygen concentration between the air in the cabin and the air inside the breathing loop. This makes this vehicle's pressurization and the ECLSS closer to a spacecraft than a conventional aircraft. The pressurization system is based on gas supplied by a pressurized air tank.

The Airbus Perlan II reached 16,000 meters or FL540 (Approx. 52,500 feet GPS Altitude), and broke the world record for unpowered flight on September 3rd, 2017 in El Calafate, Argentina. The aircraft will be targeting 27,432 meters (90,000 feet or FL900) during the summers of 2018-19. This paper will present an overview of the systems to keep the pilots alive while flying in the stratosphere with low atmospheric temperature and pressure as well as a review of the testing performed both in the ground and inflight.

Nomenclature

AT = Atmosphere
CO2 = Carbon Dioxide
C = Celsius
d*t* = time step
ELSS = Environmental and Life Support Systems
FL = Flight Level
Ft = Feet
h = height
i = time index during navigation
KM = Kilometer
kPa = Kilo Pascal
L = Liters
M = Meters
O2 = Oxygen
OAT = Outside Air Temperature
PA = Pressure Altitude
PPM = Particles Per Million
PSI = Pounds per Square Inch
RH = Relative Humidity
SL = Sea Level (pressure)
STEM = Science, Technology Engineering, , Mathematics
T = Temperature
TUC= Time of Useful Consciousness

1. Background

The Airbus Perlan II is a stratospheric fixed wing vehicle. The purpose of the aircraft is to conduct high altitude aerodynamics investigation, atmospheric and advanced aircraft system research and exploration. Additional objectives are to conquer the glider and fix wing aircraft altitude records and to educate, motivate and stimulate students, promoting Science Technology Engineering and Math (STEM) education.

The project began in 1992 with the Perlan I. This culminated with the unpressurized vehicle reaching 15,850 meters, FL520 (52,000 Ft) in August 2006. After the record flight the pilots Einar Edelvodson and Steve Fosset decided that going higher was possible and likely, however the combination of an unpressurized aircraft and pressure suit was not a suitable solution for a higher altitude flight. The decision was made to design and fabricate the pressurized Perlan II vehicle.

The Perlan II vehicle uses two different but complementary systems for ECLSS. This is a new and innovative technique. For pressurization, the Perlan II utilizes a closed loop air system, and for pilot breathing the vehicle incorporates a near 100% Oxygen rebreather system. Figure 1 depicts the Perlan II aircraft overall shape and dimensions.

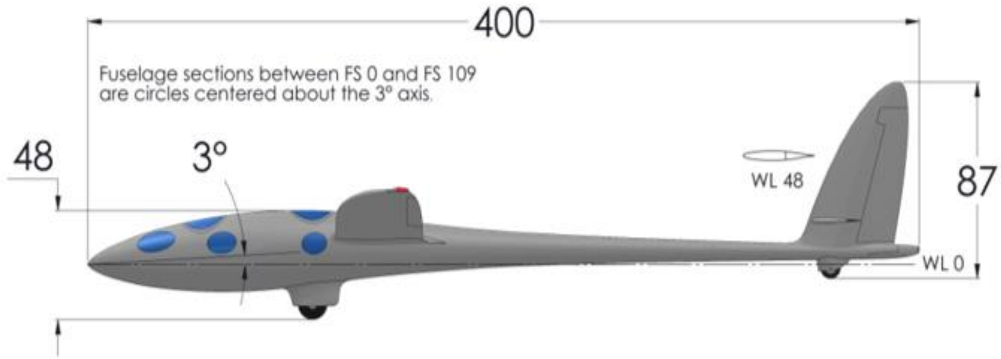

Figure 1. Perlan II dimensions

2. The Challenges and Requirements

The main challenges of the project are the discovery of stratospheric wave patterns and behavior as well as the ECLSS for an air vehicle flying in this unforgiving environment. Understanding the behavior of the stratospheric air currents and how to use them to develop flight techniques to allow the vehicle to climb inside the air masses is the "engine" that powers the Perlan. Keeping humans alive and in relative comfort is the second challenge, and this paper presents a general view of how this is achieved in the Perlan II. The vehicle requires a broad flight envelope starting at Sea Level (S.L.) and reaching 27,432 meters , FL900 (90,000 ft.) with a range of temperatures from +50 C to -80 C (122 F to -112 F) including a relative humidity levels from 10 % to 99%. Additional challenges are the lack of physical space, restricted weight budgets and limited battery power without the possibility of recharging. Funding, as in any project, is also a limiting factor as the Airbus Perlan Project is a not-for-profit endeavor.

The Perlan II requires a flight envelope from SL to 27,432 meters (90,000 feet) while keeping the occupants in enough comfort to execute their mission, up to 8 hours in duration. Another challenge is a lack of physical space for plumbing, valves and controllers. Risk mitigation is a challenge as redundant systems require space, power and weight. Working in an unheated cabin is problematic for the occupants as well as for the electronics and avionics inside. Innovation and cross industry solutions made for the results that are allowing the Perlan to safely fly into the stratosphere.

Table I Some of the requirements for the Perlan's ECLSS

FLIGHT ENVELOPE (Outside)	CABIN ENVELOPE (Inside)	CABIN ENVELOPE TARGET
Sea Level (Min pressure alt.)	Sea Level + 1.0 PSID (15.7 PSI)	1.0 – 8.7 PSID
FL900 (Approx. 90,000 feet)	15,000 Feet (6.5-7.5 PSI)	MAX. 15,000 feet
Max/Min Temp: +50 C/- 80 C	+45 C to -25 C	+30 C to -20 C
AIR Pressurization/ O2: 21%	Max/Min O2: 26% - 20%	23-21%
AIR Pressurization/ CO2: Min	Max/Min CO2: 9,000 – 0 PPM	2,000 - 400 PPM
AIR Pressurization/RH:0.1-0.9 %	Max RH: 98%	Below 80%
Rebreather Loop/ O2: 100%	Max/Min O2: 99% - 75%	Above 90%
Rebreather Loop/ Temp : Cabin	Min Temp: Above 1 C	Above 1 C
Rebreather Loop/ CO2: Min	Max/Min CO2: 4,000 – 0 PPM	2,000 - 400 PPM

Note: There are other requirements not included in this paper, such as radiation, UV rays, ozone, exposure and physical and physiological requirements. During manned initial testing some of the challenges were humidity and temperature control, condensation and O2 levels inside the cabin.

3. Rebreather:

The rebreather is a closed loop system. The main elements are: CO_2 Scrubber canister and cartridge, artificial lung, face mask, valves, heaters, hoses, sensors, and HP O_2 Tank and its regulator. Additionally a supplemental O_2 emergency system is connected to the system utilizing a military CRU60 valve/regulator and HP O_2 Tank with its valves and hoses.

The life support system has no electricity or electronic parts required for its operation, however CO_2 and O_2 sensors are incorporated to monitor the levels inside the loop. Pressure and temperature from the normal/main tank are electronically monitored. Flow rates are calculated to monitor system health. The rebreather loop contains near 100% O_2 concentration. The artificial lung adds O_2 via valve injections from the main tank, as the system requires more volume. The injections of O_2 are based on volume and no other parameter.

The O_2 enters the artificial lung travelling to a modified MBU 20 face mask reaching the pilots' lungs. On the exhaust cycle the flow travels to the CO_2 scrubber canister were CO_2 is extracted, and from there back to the artificial lung. If the volume drops, an injection of O_2 is introduced into the system. If too much volume of gas is inside the rebreather system the artificial lung will vent the extra gas inside the cabin therefore raising the volume of gas inside the cabin and also the O_2 levels. This could happen in instances where the pilot is using rapid breathing due to a large physical demand. So far this has not been a problem. The system is capable of accommodate all demands from the pilot.

The system is simple with the only main moving part being the rubber bladder inside artificial lung. Leakage is minimum and almost all of it originates at the face mask. The modified MBU 20 face mask has one way valves on the inhale and exhale intake loops. The face mask has a very tight fit to the contour of the pilot's face. The MBU20 was modified to add drinking water and liquid food to the pilots' mouth.

To start the rebreather we use a technique known as "purging." The exhale hose is placed outside the vehicle, allowing the exhausted air to be vented outside the loop while inhaling only from the rebreather; therefore the new introduced O_2, as the system has low volume and no return air is being introduced during purging. Doing this allows for the loop O_2 levels to raise from the initial air trapped inside the loop and to vent air, and for the O_2 level to rise inside the loop. After approximately 2 minutes, the O_2 level inside the loop is in the 90-95% level and the exhale port is connected to the loop, thus closing the rebreather loop.

Figure 2. Rebreather system

Breathing while wearing the face mask and rebreather is easy and does not present any impediment with no supplemental training or technique required. The face mask seats more tightly than in normal operations in other aircraft applications, however it does not present a physical impediment or discomfort.

One of the main challenges encountered early during testing was the leakage from the face mask and the rebreather loop. This was enough to raise the system and cabin to a higher than 21% O_2 content in the cabin. This resulted in reaching our maximum allowed O_2 cabin air content of 26% before the end of the flight. After investigation and some modifications to the mask and loop, the O_2 levels inside the cabin are raising between 2-3% in a normal duration flight, well within our preset limits.

The rebreather has the challenge of managing water from respiration inside the breathing loop. The rebreather has a sponge inside the exhalation chamber, which traps a substantial amount of the total water in the system. The rest of the water ends up trapped inside the hoses and the face mask. For the six to eight hour mission duration this has not been a substantial challenge to comfort or operation. One concern was that the trapped water will freeze, however due to the body heating and the chemical heating from the CO_2 scrubber the temperature inside the breathing loop remains above freezing.

4. Pressurization system

The Perlan II utilizes a closed loop pressurization, accomplished via a supply of air (21% O2) from a pressure air tank. This air has been de-humidified to a less than 1% RH content, the air tank provides air to a pressure of approx. 1.0 PSI above outside pressure, controlled via digital pressure controller.

The pressurization has the following elements; A high-pressure air tank and its regulator, electronic in and out flow valves, electronic cabin controller, electronic regulator valves, manual in and out flow valves, sensors, heaters and hoses. See figure 3.

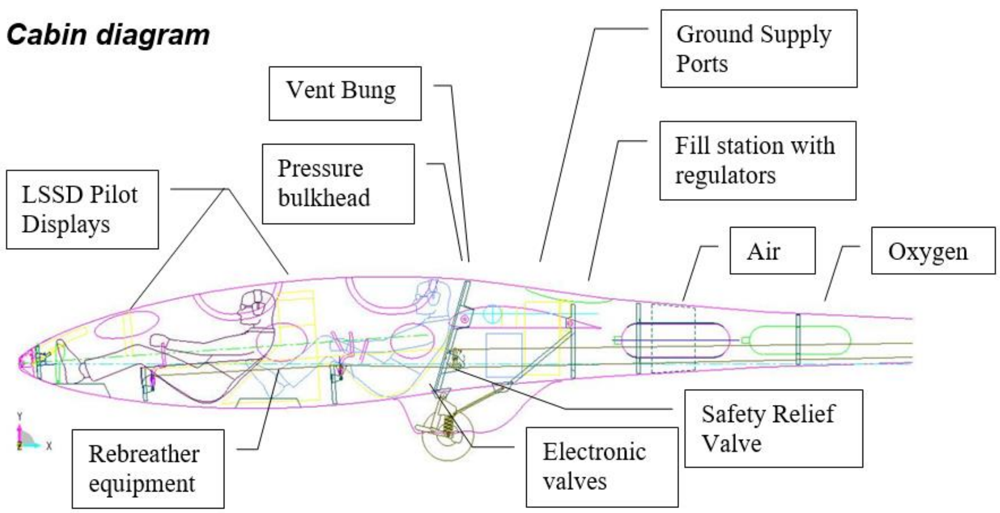

Figure 3. Perlan II Cabin Diagram

The air leaves the tank with a step down regulator from 12,755 kPa (1850 PSI) to a 207 kPa (30 PSI) line pressure. From there it reaches an electronic-pneumatic valve that allows air injections into the pressurized cabin as commanded by the electronic cabin altitude controller; this allows air inside the cabin to always keep a differential pressure of a minimum of 1.0 PSID above the outside atmospheric pressure. The vehicle leaks a small amount of air out, approx. 1 L/min. When the cabin controller senses a drop of pressure of 0.69 kPa (0.1 PSI), it allows an injection of air into the cabin. The air injection schedule depends on rate of climb or descent, temperature differential, humidity and other parameters. The maximum cabin differential is 8.7 PSID

Manual valves are available to the pilots to add air manually, or to vent air out. This manual system circumvents the automatic electronic system, however it is possible to have both working out of sync, therefore if more than a small amount are to be added or subtracted to the cabin the automatic mode should be un-powered while using the manual valves. Manual valves are only used for a malfunction; under normal conditions the automatic cabin controller covers the full flight profile envelope.

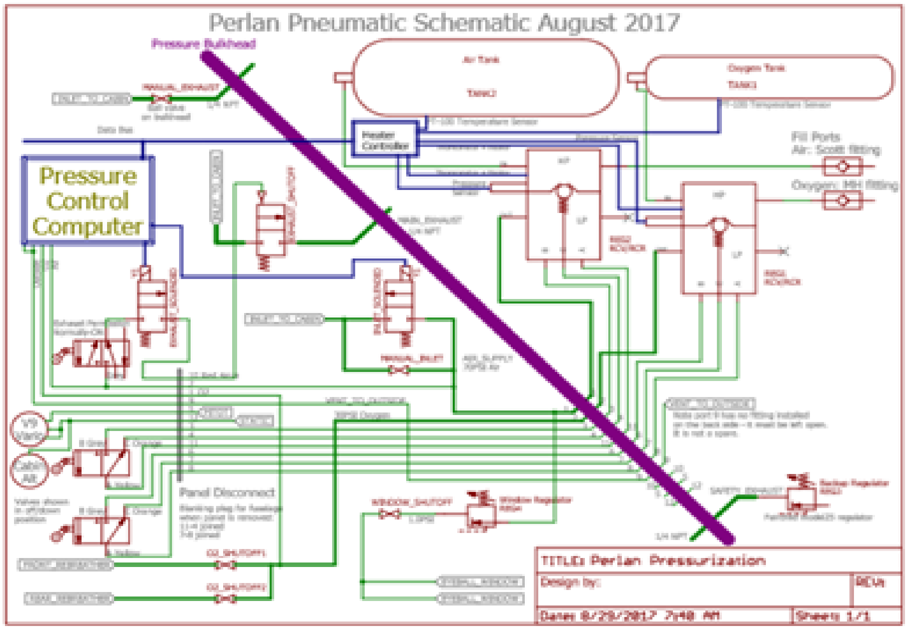

Figure 4. Perlan II Pressurization Schematic

5. Testing

Without going into great detail of all tests conducted, this section will cover some of the most significant tests performed on the ground and inflight.

Several tests were performed in the ground both inside the Perlan and outside for individual components, as well as the entire system together. The tests inside the Perlan were conducted both pressurized and unpressurized. The ECLSS was tested in incremental altitudes in flight.

An initial 4 hour rebreather test outside the Perlan was performed to verify O_2 consumption and levels, and CO_2 levels. The results show that we have enough O_2 and CO_2 scrubbing for approximately a 20 hour mission. The CO_2 levels were stable at under 1,500 PPM, and O_2 in the loop level was 88-92% throughout the test. The remaining gases inside the loop (8-12%) were not measured, but it is suspected to be mostly Nitrogen.

A cold soak test to -19° C (-2.2° F) with rebreather and facemask for a 2 hour test duration inside an industrial freezer was performed with an engineer. The results were positive, with temperatures in the breathing hoses in the range of 15-17° C, -9 to -7 C° in the breathing chamber, and 1-2 C° inside the CO_2 canister. All these temperatures were measured at the end of the test. The test was relevant, as the assumption was that the Perlan's cockpit will not go below -20° C and this will be for a period no longer than 2 hours. Humidity freezing inside the loop and blocking the flow of gas was the main concern. Visual inspection showed no ice or blockage, however some condensation turned into frost on top of the breathing chamber.

The exothermic CO_2 absorption in the scrubber cartridge was obviously heating the cartridge, as shown by the positive temperature change on the outlet side of the cartridge. The fuselage testing took place in an engineering production compliant unit. The test resulted in a predicted failure point of 180 kPa (26 PSID).

A second test for pressurization differential was performed, this time, on the flight production prototype and a 80.6 KPa (11.7 PSID) target was successfully targeted. This is approx. 1.35 times the maximum differential for the pressurization.

A dehumidifier selection test was performed inside a sealed bathroom with two desiccant materials, zeolite and silica gel. The test compared the amount of water absorbed. Approx. 572g of Zeolite and 531g of silica gel was used. The zeolite absorbed a larger amount of water, approx. 160g in 1 hour and 16 minutes vs. the 90g in 3 hours and 15 minutes of the silica gel. Zeolite was chosen for humidity control in the Perlan.

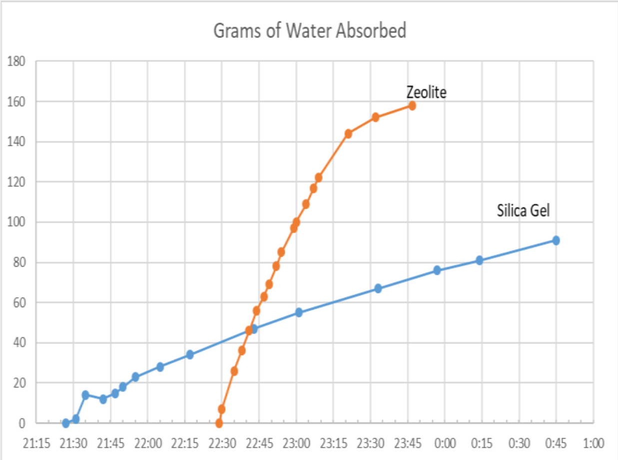

Figure 5. Water absorved vs. Time Test

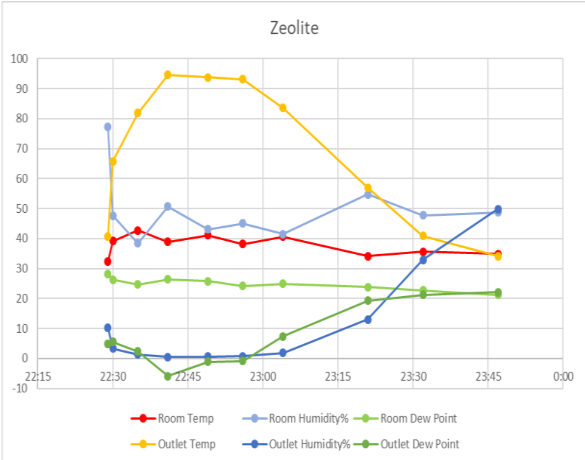

Figure 6. Zeolite performance

Several tests were completed inside the Perlan, on the ground; both unpressurized and pressurized. The rebreather performance was measured for CO_2 content, oxygen consumption, oxygen leakage rate into the cabin, internal temperature and pilot comfort. All test were satisfactory with the exception of oxygen leakage into the cabin. This issue was corrected by replacing a valve.

The testing on the pressurization provided data that was analyzed for pressure and air leakage, cabin controller and air rates, temperature and humidity. Humidity control was and is the biggest challenge. Initially the Perlan cabin reached 95-98% relative humidity approximately 1 hour after the hatches were closed. After installing the zeolite container with a recirculating air fan the humidity reached a maximum value of 80-90% during flight.

Testing on the ground, pressurized yielded very similar results to using the rebreather while unpressurized. Several pressurized tests were conducted while not wearing the rebreather to test CO_2 increase in the cabin. The results were a rise in CO_2 from below 500 PPM to above 10,000 PPM in approx.12-14 minutes. This test gives an approximation to the flight crew on the duration allowed for possible rebreather malfunction while pressurized at altitude and a subsequent emergency descent.

In May of 2018, the team performed a partial ambient pressure test at the Southern Aero-Medical Institute (S.A.M.I.) with the collaboration of Dr. Paul Buza, MD. The test objective was to test the performance of the rebreather at an altitude of 12,497 meters (41,000 feet), and to activate the Emergency Descent System, and to descend at a high rate inside the Hypo-Hyperbaric chamber. The test was similar to a lack of cabin pressurization due to a pressurization malfunction. The test was successful to provide adequate pressure and oxygen to the pilot. The pilot was provided approximately 95% of O_2 inside the loop at apogee and maintained a 92-94% SpO_2 while performing cognitive test and activating the bailout O_2 tank and system. The Emergency Descent System provided 99% O_2 inside the loop and 98% SpO_2 to the pilot. The test subject was monitored for SpO_2, O_2 in the breathing loop, heart rate and temperature. Meanwhile, the cabin was also monitored for temperature as well as altitude, and rate of climb and descent. The test included two video systems; one for the subject and one for the equipment.

Finally, several flights were completed with a built-up approach to testing, starting at low altitude, unpressurized while breathing via the rebreather. Rather than discussing those initial flights the focus will be on flight number 38, a high altitude record flight (see below).

6. Record Altitude Flight

On September 3rd, 2017 in El Calafate , Argentina, the Perlan II aircraft and its crew flew to the highest altitude to date; this was the longest and highest the team has ever flown. The record flight had a flight duration of 6 hours and 30 minutes, the total time breathing via the rebreather was approx. 7 hours and 15 minutes (including ground time). The test flight objectives were to fly to an altitude of 53,000 feet and stop during climb at 35,000, 40,000, 45,000 feet to performed flutter, flight dynamics and systems tests. All were performed successfully.

As the longest and coldest flight to date, consumables usage was the main factor limiting further exploration. A further limiting factor was the test point for the flight was completed and return to base was executed as per the test plan. Just before reaching maximum altitude, with maximum pressure differential, the remaining air tank duration was 6.3 hours, predicting exhaustion at 17 hours and 15 minutes.

After leaving maximum altitude, the air usage is reduced as the pressure differential is reduced. During the re-pressurizing for landing, air usage increased again. Remaining pressurization duration dropped precipitously to 0.6 hours, predicting exhaustion at near the landing time. The air tank finished the flight at 20% due to 9% of the air tank being used for re-pressurizing.

The battery finished the flight at 19%. Since the battery measurement is not exact, we want to have a reserve remaining at landing. A battery model based on this flight shows we should consider 24% as the minimum battery level to continue climbing. This allows for a one hour descent. For 2018, the battery size in total amperage was increased by 50% to 150 amp-hours.

Battery usage was influenced by the flutter heating and by turning off the equipment bay heaters during the descent. Each flutter heat episode uses about 1% of the battery capacity. Turning the heaters off is detrimental at that phase of flight.

Below are several charts from onboard sensor information: (The solid brown is the Terrain)

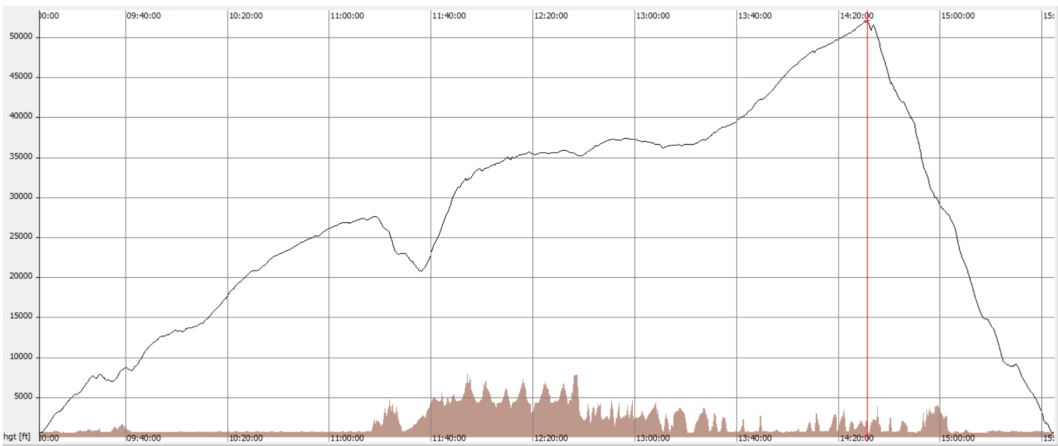

Figure 7. Altitude (Feet) VS Time (UCT) September 3rd, 2017

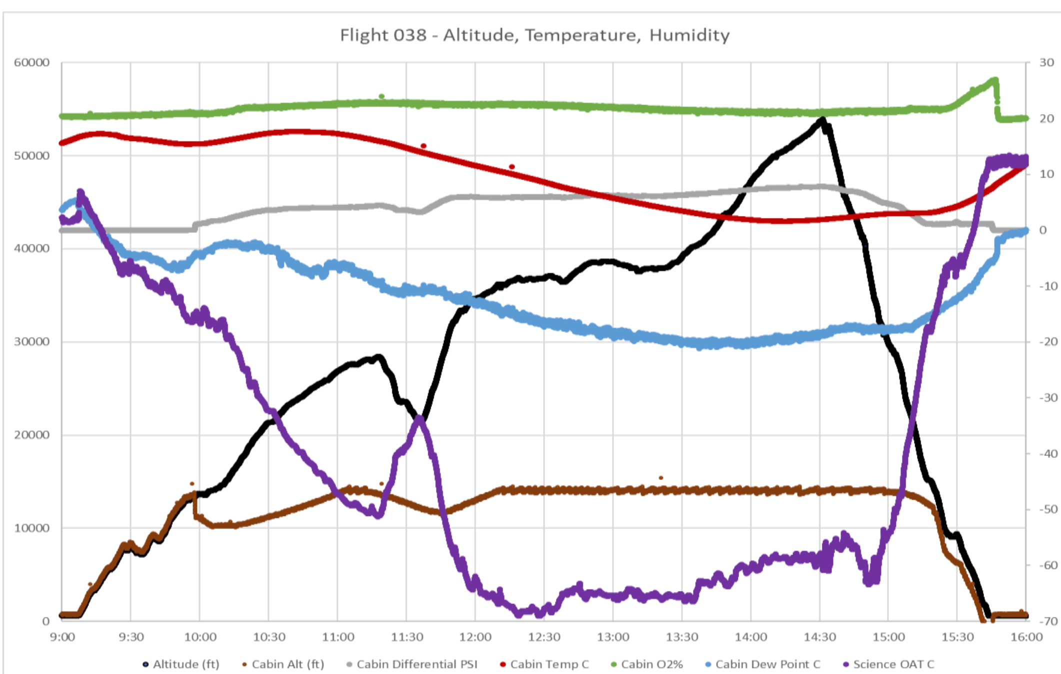

Figure 8. Sensors readings

Notice cabin O2 is stable during the flight near 21-22% O2 to Air concentration. Cabin differential pressure peaks approx. 51.8 kPa (7.5 PSID) at apogee.

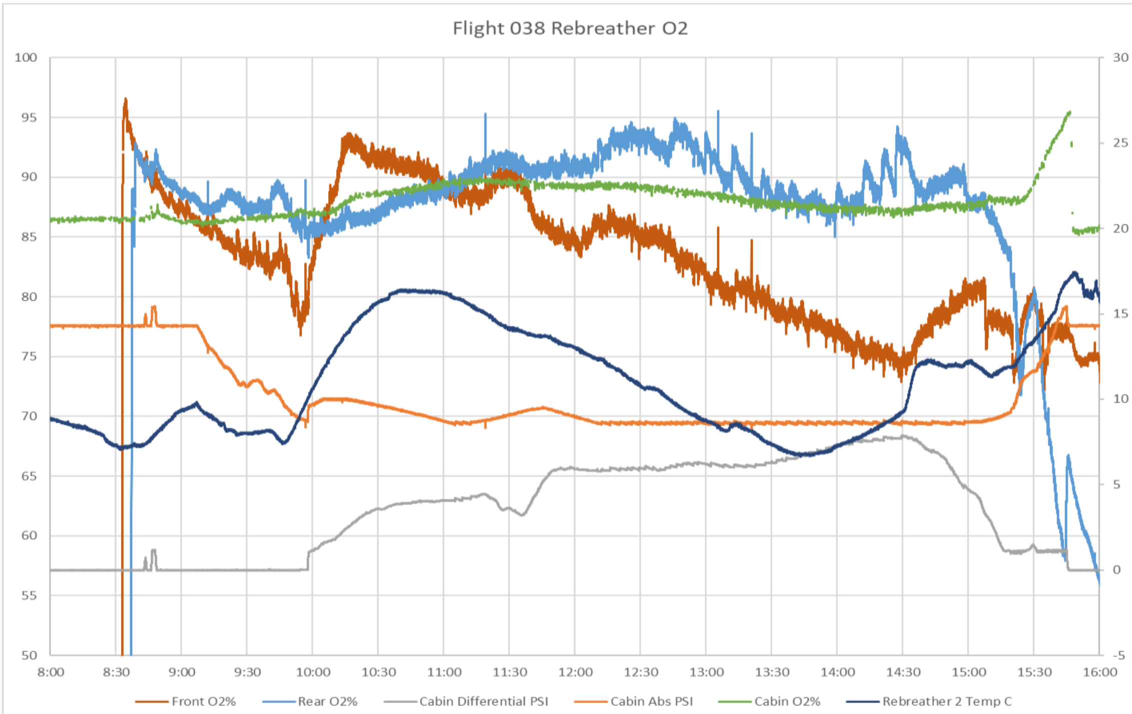

Figure 9. Rebreathers O2 - Sensors

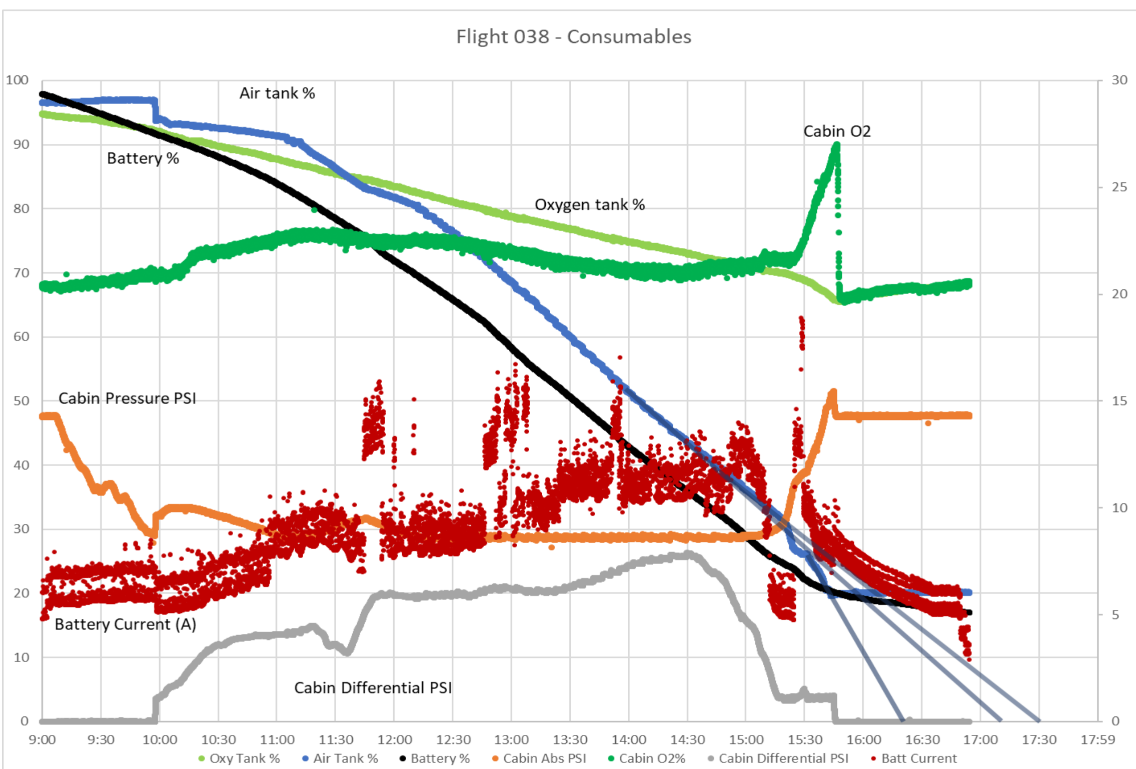

Figure 10. Consumables Table

Battery life at landing was just under 20%. This year we added 50 amps to the 100 amp capacity used in 2017. This will ensure a 25% battery capacity at landing on future flights. Cabin internal pressure was stable for most of the flight, near 62.1 kPa (9.0 PSI)

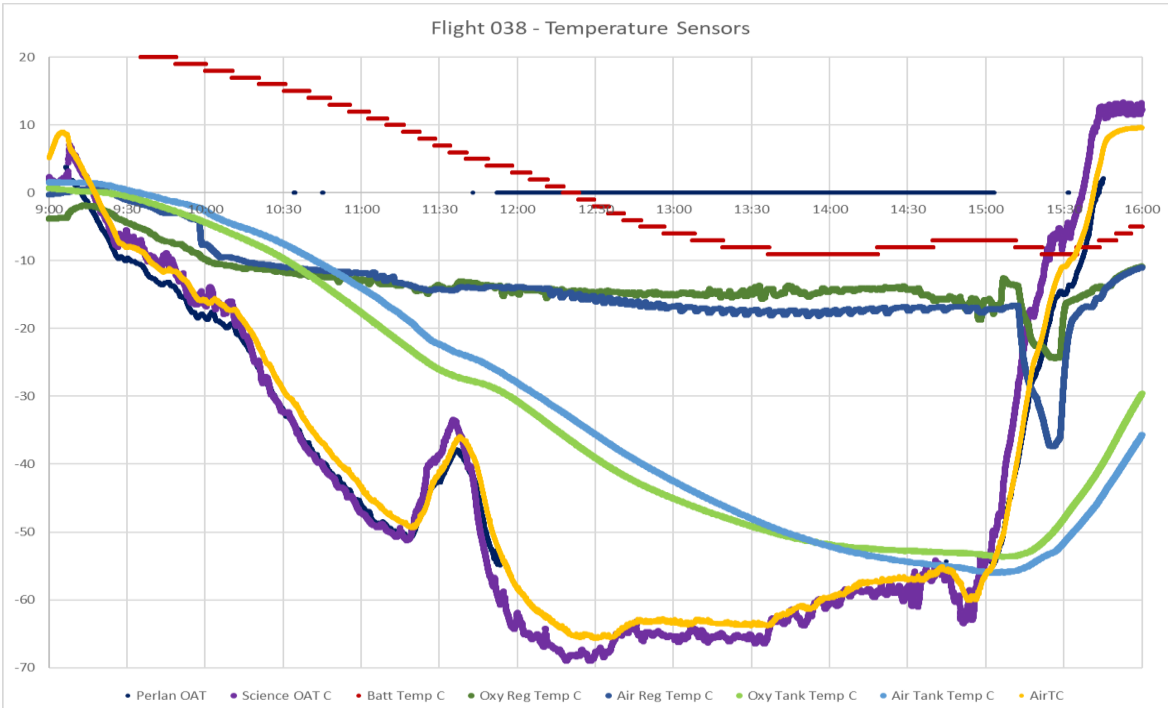

Figure 11. Temperature Sensors vs Time

The drop in temperature in the air and oxygen tank regulators is due to the heaters being turn off to save battery and to test the temperature drop change over time.

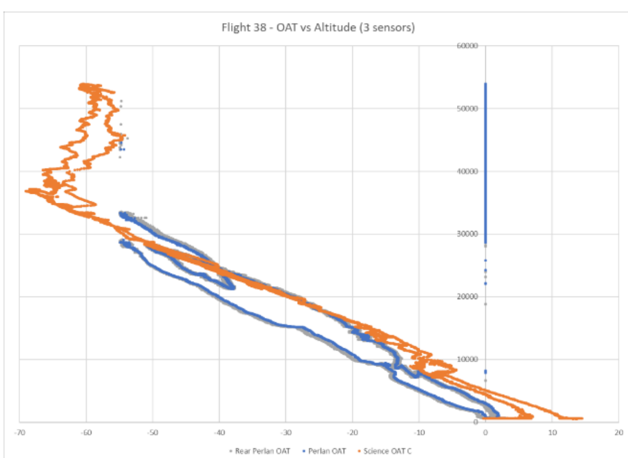

Figure 12. OAT vs Altitude

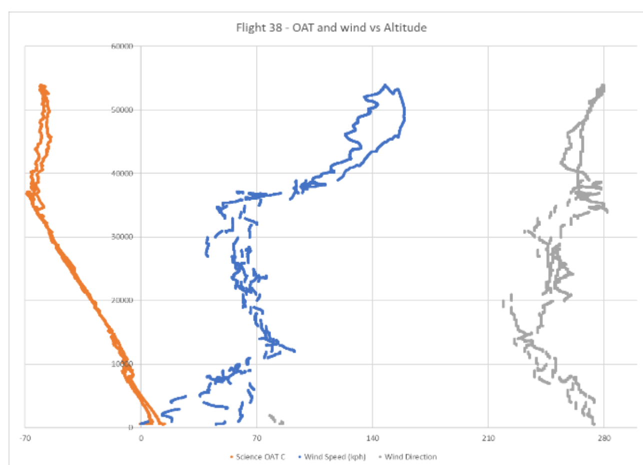

Figure 13. OAT & Wind vs Altitude

Outside air temperature reached a minimum of -68.97°C (-92.15 F) at 11,235 meters (36,858 feet) before warming up in the stratosphere. Around southern Argentina and during the winter months the Tropopause can be found as low as 6,400 meters (21,000 feet) and as high as 11,583 meters (38,000 feet).

7. Conclusions

The Perlan ECLSS has been designed based on an existing Biomarine rebreather originally designed for mining and with simplicity in mind. The results have been exceptionally good for a new design. The system is easy to use, comfortable, and will outlast the required mission duration by as much as 200%. All of the issues encountered during the initial testing were resolved and the minor remaining issues do not cause any impediment to our 8 hour duration mission.

The dual atmosphere pressurization and rebreather system with air inside the cockpit and near 100% oxygen for the occupants in a closed loop pressurization vehicle was a concern in the beginning of the project, however after extensive testing the results are that the dual system works well together with only minor issues.

The hatches were a point of possible air leak due to temperature change and deformation around the seals. After the end of the 2017 flight campaign it was decided to remanufacture and improve the design of the hatches. In 2018, the Perlan will be flying with new hatches. This will improve possible deformation issues.

During April 2018, the Perlan team added new, improved carbon dioxide scrubber canisters, check valves and an improved emergency descent system. This was tested at S.A.M.I. with a positive outcome.

The Perlan II aircraft will be targeting the goal of reaching 27,432 meters (90,000 feet) in the summer months of 2018 and 2019. For now, our testing has occurred up to a flight altitude of 16,460 meters (54,000 feet) pressure altitude.

References

1. Biomarine. Perlan Installation Manual. Internal Perlan Document prepared by Biomarine for the Perlan Project.

Acknowledgments

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