OBOGS INTEGRATION INTO A TURBO-PROP TRAINER AIRCRAFT

Mr D. Richardson
Senior Systems Engineer, Trainer Aircraft Systems Engineering
Pilatus Aircraft Ltd, 6370, Switzerland
Tel +41 41 6196777 / fax +41 41 6196452 / e-mail: drichardson@pilatus-aircraft.com

Keywords: *OBOGS, Oxygen system*

Abstract

The state of the art of modern On-Board Oxygen Generation Systems, OBOGS, has advanced to the point where these systems are both financially and technically viable for use in turbo-prop trainer aircraft.

Lifecycle costs for OBOGS systems are significantly lower than those for a conventional gaseous oxygen system.

Operational advantages include the removal of oxygen endurance limitations from aircraft operations and improved aircraft and maintenance safety due the reduced use of high-pressure oxygen.

The technical difficulties in introducing such systems to small turbo-prop trainer aircraft are primarily those concerned with ensuring the system operates successfully throughout the flight envelope whilst subject to the particularly low compressor bleed pressures available from the small turbo-prop power plants used in these aircraft.

This paper demonstrates the lifecycle savings possible with the modern OBOGS. It describes the Pilatus development programme to integrate a Litton Life Support OBOGS onto the Pilatus Modular Trainer aircraft, including the technical problems, which were overcome on the way to successfully certifying the system for use.

1 Introduction

The Oxygen system schematic shown in Figure 1 provides an overview of the system configuration. The main elements of the system are the heat exchanger, the primary shut-off valve, the water drain bolt, the oxygen concentrator, the oxygen breathing regulators, the flow indicators and the seat emergency oxygen set. The function of each of these components is described below.

2. Description and Function of System

The function of the heat exchanger is to condition engine compressor bleed air to a temperature acceptable for the oxygen concentrator. Correct function of the oxygen concentrator requires a maximum steady state air inlet temperature of 60°C. Bleed air from the engine P3 compressor bleed air off-take is passed through the heat exchanger, where it is cooled by a continuous flow of ambient air via a NACA intake in the upper surface of the engine cowling.

The function of the shut off valve is to close off the system when it is not operating, or when the aircraft engine is not running, to prevent water and other foreign objects from entering the system. It also provides a means to shut off the system in the event of a fire in the engine compartment.

The function of the auto drain bolt is to allow any condensation water that has accumulated in the pipe low point to be blown out of the system when the pipe is pressurised.

The oxygen concentrator produces concentrated oxygen breathing gas by means of molecular sieve technology based upon the nitrogen absorption and desorbtion properties of Zeolite (alkali metal alumino-silicate) material. The function of the concentrator is to provide the breathing regulator with a supply of clean, dry, oxygen enriched gas at a concentration appropriate to the aircraft altitude.

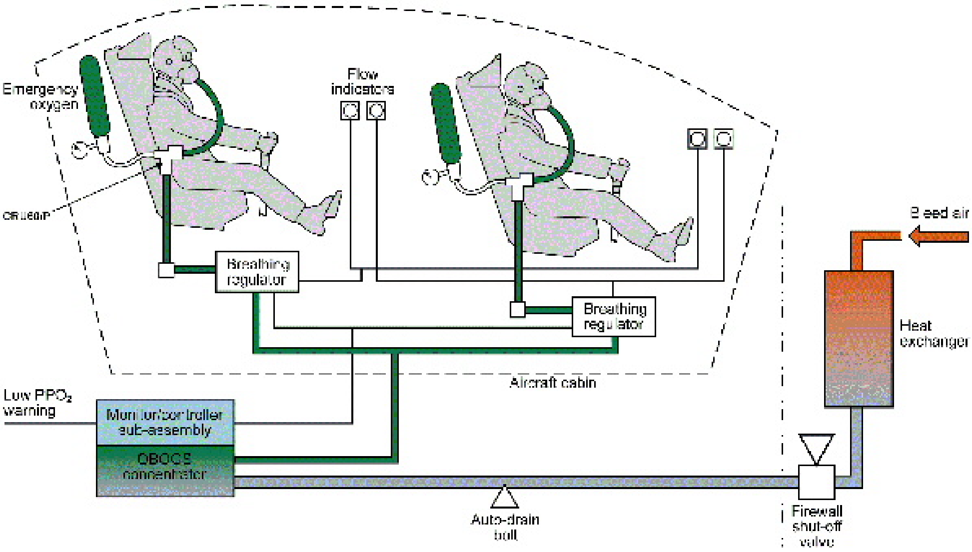


Figure 1: System Schematic

2.1 System Operation

Cooled bleed air from the heat exchanger flows into one of two oxygen beds which operate as an alternating pair so that when one bed is pressurised, adsorbing nitrogen and producing oxygen-enriched product gas, the other is venting to ambient and desorbing nitrogen from the previous pressurisation period. This desorbtion is aided by passing a small reverse flow of oxygen-enriched gas from the output or product end of the pressurised bed. The two oxygen beds are cycled alternately between the pressurisation, or oxygen-production mode, and the venting, or nitrogen-purging mode. This cycling is achieved by the movement of a slide valve in the bed outlet manifold.

The concentrator also contains the monitor/controller sub-assembly. The functions of this sub-assembly are to sense both the output gas oxygen concentration and aircraft altitude and to control the cycle speed of the concentrator in order to produce the required oxygen concentration for the given altitude. This sub-assembly also provides a warning to the aircraft's central warning system should either the oxygen partial pressure fall below the required level or the system's built-in health monitoring sense a system failure.

The breathing regulator has the following functions:

To provide the pilot with the oxygen enriched gas from the concentrator on demand at the correct pressure for breathing.

To provide breathing gas at a pressure slightly higher than ambient in order to prevent inwards leakage of ambient air into the mask. This is termed 'Safety Pressure' and is provided from sea level up to the maximum aircraft altitude.

To provide an anti-suffocation facility such that the pilot can breathe when the system or regulator is switched off.

To provide a pilot station shut off facility.

To provide a mask 'Press to test' function which increases mask pressure to allow mask fit to be adjusted/checked as well as verify all hose connections.

To provide initiation of the concentrator Built In Test (BIT) functions and 'maximum concentration or normal concentration' mode switching. To provide a breathing gas 'flow' signal to the oxygen flow indicators.

To provide 'emergency' pressure when manually selected.

To prevent mask overpressure.

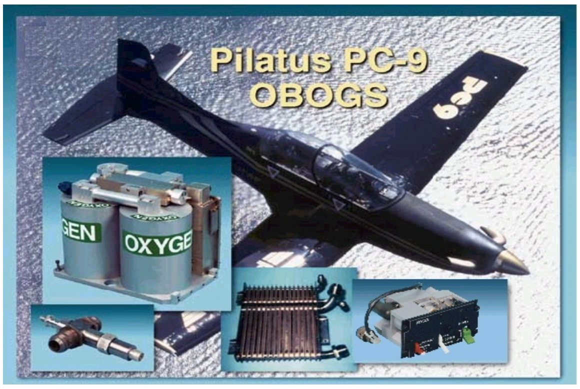
The function of the flow indicators is to provide visual indication to each pilot of the flow and no-flow of the inspiratory gas. The indicator will normally alternate between a flow indication and a no-flow indication in response to pilot inhalation and exhalation. A constant 'flow' indication indicates a leak and a constant no-flow indication indicates a blockage, failed system or improper mask connection to the aircraft.

With the regulator/system switched on and operating in the NORMAL mode the concentrator cycle time, and hence delivered gas oxygen concentration is controlled from the concentrator's internal monitor/controller sub-assembly. The monitor/controller sub-assembly is an embedded software (firmware) controlled device, which monitors the Oxygen Concentration of the output gas via a Zirconia cell oxygen sensor and monitors the aircraft altitude via an internal pressure transducer. The firmware calculates the Partial Pressure of Oxygen (PPO_2) compares the PPO_2 and altitude to a pre-programmed schedule and adjusts the cycle timing of the concentrator to match the schedule. At altitudes above 22,500 ft the concentrator is automatically switched to the maximum concentration mode.

The firmware has a low PPO_2 warning limit set at 182 mmHg (part of Continuous BIT function) such that if the output gas drops below this limit for any reason then an internal warning relay opens to cut off a 28 Volt supply to the aircraft's central warning system and initiate an amber OXYGEN caption. There is a minimum 6 Second delay, calculated as a rolling average, built into the Low PPO_2 warning circuit in order to eliminate spurious warnings.

The Oxygen system has a number of test and Built in Test (BIT) functions these are

- Mask Test
- Power-up BIT
- Continuous BIT
- Initiated BIT
- Maintenance BIT



3 Operational advantages of OBOGS

3.1 Life Cycle Cost Comparison

Although initial purchase costs of these systems remains higher than that of an equivalent conventional gaseous oxygen system the lifecycle costs of the OBOGS is considerably lower than those for the gaseous system. Additionally some operators may eliminate all ground oxygen support infrastructure.

EXAMPLE:

OBOGS VERSUS GASEOUS O_2 SYSTEM
LIFE CYCLE OPERATING
CALCULATIONS

FLEET SIZE = 50 Aircraft

BASIC INPUT DATA

Life :- 20 Years
Flight Hrs Per Aircraft Per Year :- 250 Hrs
Sortie Duration :- 1.5 Hrs
Man Hour Rate :- 70 Sfr/Hr
All costs approximate at 1998 Economic values

GASEOUS SYSTEM

INSPECTION COSTS

No. of Regulator Inspections/Aircraft/Year:- 1 (Bi-annual Bench Test)
No. of Regulator Inspections/Aircraft/Life :-20
No. of Regulator Inspections/Fleet/Life :- 1000
Man Hours Per Inspection :- 3
Total Man Hours Per Fleet Per Life :- 3000
Total Costs Per Fleet Per Life :- 210000 Sfr

REPLACEMENT COSTS

Number Of Bottles Per Aircraft :-	2
Bottle Cost :-	1874 Sfr
Bottle Cost Per Aircraft :-	3748 Sfr
Bottle Cost Per Fleet :-	187400 Sfr

HYDROSTATIC TEST COSTS

No. of Bottle Inspections/Aircraft Life:- 13.33
Internal Inspection every 3 years

Cost Per Bottle Hydrostatic Test :-	1600 Sfr
Man-hours For Removal & Replace :-	2
Cost Per Aircraft :-	21473 Sfr
Total Costs Per Fleet Life	1074000 Sfr

REPLENISHMENT

No. of Replenishments/Sortie :-	0.5
No. of Replenishments/Aircraft/Life:-	1666
No. of Replenishments/Fleet/Life :-	83333
Time Per Replenishment :-	0.5

Total Replenishment Time/Fleet/Life:-	41667
Total Replenishment Cost/Fleet/Life :-	2916667 Sfr

OXYGEN PROCUREMENT & RIG REPLENISHMENT

Number Of Cylinders Per Rig :-	4
Capacity Per Cylinder :-	7500
Capacity Per Rig :-	30000
Capacity Per Aircraft Bottle :-	1350
Total Capacity Per Aircraft :-	2700
No. of Aircraft Replenishments/Full Rig :-	11.1
No. of Ground Rig Replenishments:- per Fleet/Life	7500

Number Of Bottles/Fleet/Life :-	30000
Cost Per Bottle :-	35.4 Sfr
Bottle Cost Per Fleet Per Life :-	1062000 Sfr
Man Hour Per Rig Replenishment :-	1
Replenishment Man Hour/Fleet/Life :-	7500
Replenishment Labour Cost/Fleet/Life :-	525000 Sfr

Total Replenishment Cost Per Fleet Per Life :-	1587000 Sfr

Total Life Cycle Operating Cost of Gaseous System:- 5,974,733 Sfr

OBOGS

INSPECTION COSTS

No. of Filter Changes/Aircraft/Year:-	0.4
No. of Filter Changes/Aircraft/Life :-	8
No. of Filter Changes/Fleet/Life :-	400
Man Hours Per Filter Change :-	1
Total Man Hours/Fleet/Life :-	400
Total Costs/Fleet/Life :-	28,000 Sfr

DIRECT OPERATING COST

Total Cost Per Aircraft/Flight Hour :- 0.85 Sfr
(Approx. 850.00 Sfr/Filter Change Kit)
Total Cost Per Fleet Per Life :- 212,500 Sfr

Total Life Cycle Operating Cost Of OBOGS :- 240,500 Sfr

Life Cycle Operational Saving :- 5,734,233 Sfr

Note that this does not account for unplanned maintenance actions. However quoted Mean Time Before Failure (MTBF) figures for OBOGS equipments generally exceed those quoted for gaseous systems.

For the fleet of 50 aircraft the delta cost for initial system procurement of an OBOGS over a gaseous system would be approximately 1,500,000 Sfr.

3.2 Safety

3.2.1 Elimination of recharging

The safety of the aircraft is improved by the reduction of use of high-pressure gaseous oxygen. Operations with high pressure gaseous oxygen (GOX) are at their most hazardous during system recharging when there is the greatest risk that GOX may come into contact with grease or oil. In-flight GOX leakage is another significant hazard. OBOGS eliminates the requirement to regularly recharge GOX and thereby reduces the risk to maintenance personnel. Another benefit of this aspect is the removal of the requirement for airbases to store and transport large quantities of GOX.

3.3 Endurance.

Since traditional gaseous oxygen systems contain a finite quantity of gas, aircraft using such systems are limited in their operating time before replenishment is required. Although this is the same problem associated with the requirement to refuel it is generally understood that fuel is readily available at almost all airfields whether civil or military. Supplies of high-pressure oxygen are not as generally available. This introduces operational problems and limitations when operating away from base or transiting long distances between bases.

Since OBOGS generates the required oxygen during flight there are no operational limitations.

4 Development Programme

The unit vendors qualified the individual components. The component testing included altitude testing of the concentrator and regulator with simulated input pressures and temperatures and simulated output demands. The breathing regulators are man-rated with live subjects under strictly controlled conditions.

Once the full system was installed on the aircraft, integration testing commenced. The testing consisted of a series of ground tests and a series of flight tests with a fully instrumented aircraft. The purpose of the testing was to ensure that the installed system functions correctly throughout the entire flight envelope of the aircraft.

The test aircraft and system was instrumented with sensors to monitor the following parameters:

Bleed air temperature
Bleed air pressure
Heat exchanger inlet temperature
Heat exchanger inlet pressure
Concentrator inlet temperature
Concentrator inlet pressure
Concentrator outlet temperature
Concentrator outlet pressure
Breathing regulator inlet temperature
Breathing regulator inlet pressure
Partial pressure of Oxygen (product gas)
Engine bay temperature
Concentrator bay temperature
Cockpit temperature
Cockpit-concentrator bay delta pressure
Outside air temperature
Altitude
Indicated air speed
Rate of climb
Engine parameters (torque, Ng and ITT)

Data was recorded on an on-board tape recorder and also transmitted via a telemetry system such that each parameter could be viewed in real time during the flight from a ground station.

4.1 Ground testing

Ground testing was comprised of two stages. The initial stage ran the OBOGS supplied with the aircraft electrical supply but with a separate pressure controlled filtered air supply. The second stage ran the OBOGS with the engine supplying the air supply.

A number of these ground tests were conducted and the data analysed to ensure that the system was behaving as expected.

4.2 Flight testing

Flight-testing was conducted at progressively higher altitudes. At each altitude the aircraft was put through a series of exercises, which typically consisted of a climb phase (to the set altitude), a cruise phase, a throttle transient phase and an idle descent phase. When the exercises were completed successfully at each altitude the aircraft would climb to the next set altitude. On completion of the exercises at the maximum altitude the aircraft entered a long idle descent. The prolonged idle descent was seen to be the most critical flight phase due to the combination of high altitude requiring high oxygen concentrations and low concentrator inlet pressures due to engine idle bleed air conditions.

4.3 Test Results

The initial system testing raised a number of concerns in respect to system usability. On a number of occasions the BIT function caused confusion. This was analysed and found to be due to a number of causes. The pilots were sometimes unaware of when a BIT was actually taking place or whether it had been finished. Also the BIT initiation button did not have a positive feel and pilots found it difficult to know if the button had operated or not.

In order to solve these problems a new BIT philosophy was introduced and the regulator now incorporates an additional micro switch on the Test Mask switch, which initiates the BIT function at the same time as the mask test. An orange ‘BIT in progress’ light replaces the original BIT button. These changes do not affect the functionality of either the normal operation of the OBOGS or of the BIT functions. The modifications only affect the way in which the BIT is initiated and the means by which a pilot is informed of the progress of the BIT function.

Another modification introduced to the concentrator was a low-pressure switch in the concentrator outlet. This switch is used for inhibiting BIT tests until sufficient pressure is present to conduct them successfully. Additionally, the low pressure switch is used to initiate an instant OXYGEN caption in the event of gas pressure being removed from the concentrator when in-flight, i.e. engine shut down.

The other consistent criticism of the system was the original ‘heavy’ anti-suffocation valve. This has now been replaced by a pressure balanced anti-suffocation valve, which is built into the regulator. The old anti suffocation valve was an inline unit held closed by a spring. Inhalation required sufficient suction to be applied in order to overcome the spring force. The new anti-suffocation valve is built into the outlet from the regulator and only employs a very light spring. The primary means of keeping the valve closed is by means of a pressure tap taken from the inlet to the regulator. The tap supplies pressure to a piston, which holds the valve, closed when gas is supplied to the regulator. Consequently, when there is no supply gas, the suction required to open the valve is greatly reduced.

4.4 System developments

Following the successful completion of the PC-9 flight test programme a number of flights were conducted to investigate the low pressure behaviour of the system in order to gain information to aid adaptation of the OBOGS system to the PC-7 MkII aircraft which has lower bleed air pressures available. During these investigations, it was confirmed that the lower bleed air pressures produced by the PC-7 MkII were not going to be sufficient to keep the OBOGS concentrator cycling throughout the PC-7 Mk II flight envelope.

As a result of this the OBOGS manufacturer introduced a number of modifications to the system in order to improve the low-pressure performance of the system. The following details the modifications made:

Slide Valve Modification

The concentrator alternates the bleed air supply to each molecular sieve bed by means of a servo-pressure operated slide valve. The slide valve operation is dependant on the bleed air pressure supplied to the concentrator. In order to reduce the force required to move the slide valve, and hence reduce the inlet pressure requirement, the friction surfaces were modified in order to reduce area and hence the internal friction loads of the slide valve.

Purging Flow Improvements

Analysis of the flight test results by the concentrator manufacturer and subsequent low pressure testing in the laboratory it was noted that the purging of the molecular sieve beds was not always as efficient as it should be and an in-balance in the purging of the beds was noted. Since the beds were not being purged as efficiently as should be possible the oxygen production of the beds is therefore not always being maintained at the best possible output during low-pressure operation.

The bed purging was subsequently improved with minor mechanical changes to the concentrator.

Primary Shut-off Valve Drain Spring Removal.

In order to improve the available bleed air pressure at the actual concentrator inlet, the system was investigated for areas of high-pressure loss. Since the primary shut off valve was known to have a high loss, the manufacturer was requested to investigate any means for reducing the internal pressure loss of the valve and hence increase the pressures available to the concentrator.

It was found that the pressure loss of the valve could be significantly reduced by simply removing the internal spring from the drain valve. Since the spring acts on the valve head as well as the drain valve the pressure required to keep the valve fully open must also work against this spring.

The function of the spring is to keep the drain valve open when no system pressure is supplied to the valve and the valve is de-energised (closed). However since bleed air is supplied to the valve before the valve is energised open the drain valve will open first and vent any water, which may have gathered in the pipe work up-stream of the valve.

It was therefore decided that the spring was not necessary for the correct functioning of the system and that removal of the spring would improve the low-pressure performance of the system.

System Testing of Additional Modifications

The prototype hardware was modified to incorporate the additional modifications and extensively tested by the manufacturer. The modified prototype hardware was then re-installed to the test aircraft. Ground and flight-testing was conducted as before and indicated improved low-pressure performance, though this was hard to quantify for the PC-9(M) configuration (since it already had been proven to work).

The test aircraft was then re-configured with a bleed air restrictor to effectively simulate the PC-7 MkII performance. Improvements were immediately obvious since previously the OXYGEN captions had occurred consistently any time low power was selected. The occurrence of OXYGEN captions was reduced, however they still occurred when low power was combined with low airspeed indicating that the system was still not achieving high enough pressures at the inlet to the concentrator throughout the entire PC-7 MkII envelope.

The low pressures were confirmed by telemetry and further analysis indicated that the restrictor was accurately simulating the bleed air performance of the PC-7 MkII.

The conclusion of this testing was that the modifications were of benefit to the system, improving system performance for both the PC-9(M) and for the PC-7 MkII and consequently the modifications have been incorporated in all PC-9(M) production hardware.

PC7 MkII testing has continued. The low-pressure problems being solved with the introduction of a low-pressure loss dual supply pipe. Additionally further improvements to the concentrator’s concentration control firmware have been made to tighten the actual oxygen concentration to the target oxygen concentration/altitude schedule.

5 System Certification/FAR23 Compliance

The following FAR23 requirements are satisfied by the PC-9(M) Oxygen system:

§23.1183 Lines fittings and components

All components, lines and fittings of the oxygen system installed in the engine bay are either manufactured from stainless steel or are qualified as fire-resistant.

§23.1191 Firewall

This requirement is satisfied by the installation of a firewall shut-off valve in the OBOGS bleed air delivery pipe work and the use of stainless steel pipes upstream of the shut-off valve.

§23.1301 Function and Installation

It has been demonstrated that the system functions correctly and performs its intended function when installed correctly and according to equipment limitations. The system and its controls are labelled to indicate their function.

§23.1438 Pressurisation and Pneumatic Systems

The pneumatic elements of the system are proof pressure tested to 1.5 times the maximum normal operating pressure and burst pressure requirements of greater than 3.0 times maximum normal operating pressure is proven by calculation.

§23.1441 Oxygen equipment and supply

a) Certification with supplemental oxygen equipment is requested, therefore sections §23.1443 through 23.1449 apply.

b) The system has been demonstrated to be free from hazards by the equipment and system qualification and the safety analysis document.

c) The main oxygen system fitted to this aircraft is of a no-finite nature as it is an oxygen generation system. There is therefore no “quantity” of oxygen to indicate. The contents of the emergency oxygen are displayed by means of a contents gauge mounted on the bottle and visible to the pilot upon embarkation of the aircraft.

d) The demand flow oxygen equipment utilised on this aircraft has been qualified as demonstrated by the equipment qualification and the system testing. Certification of this equipment for use at altitudes above 40,000 ft is not required.

e) With the exception of the emergency oxygen set which remains off until used there is no high-pressure supply of oxygen to turn on or off. The crew can however isolate themselves from the system either by turning off both the regulators or pulling the system circuit breaker either action will result in closure of the primary shut off valve at the firewall and the concentrators internal shut off valve. The regulator off switch additionally isolates each pilot station individually by means of a shut-off valve in each regulator.

§23.1443 Minimum mass flow of supplemental oxygen

Continuous flow equipment is used as a standby and emergency system. It is installed on the ejection seats. The system provides 11 minutes supply of oxygen at 12,000 ft.

§23.1445 Oxygen distribution system

Metallic tubing is utilised for all oxygen lines with the exception of those lines used down stream of the regulator (i.e. the mask hose)

§23.1447 Equipment standards for oxygen dispensing units.

Each pilot has one pressure demand regulator and one oxygen mask. The MBU12/P oxygen mask supplied is an accepted aerospace component and covers the nose and mouth. In this application the mask is worn at all times during the flight and is retained on the face by means of two adjustable connectors attached to the helmet. The mask incorporates a microphone, which permits the wearer to communicate via the radio or intercom system of the aircraft whilst the mask is being worn.

§23.1449 Means for determining the use of oxygen

The system is fitted with breathing gas flow indicators, permanent safety pressure and a low PPO_2 oxygen warning sensor all of which indicate to the pilot whether breathing gas is available at the dispensing equipment.

6 Conclusion

By far the greatest challenge in integrating the OBOGS onto the PC-9(M) and PC-7 MkII aircraft has been solving the problems in making the system work with very low input air pressures. This task was made more difficult by the fact that these aircraft are un-pressurised which consequently required higher OBOGS performance than with an equivalent pressurised aircraft. This was successfully overcome by a combination of improvements made by the equipment manufacturer to the basic components and by changes made to the configuration of the system installation. The testing produced a large quantity of data, which consumed considerable time in analysis and required the skills of a number of engineers to establish the behaviour patterns of the system throughout the flight envelope of the aircraft. These behaviours often did not match exactly those that had been expected or witnessed in test cell experiments. This provided a strong lesson in accurately simulating operational conditions at an early stage in component development.

The PC-9(M) OBOGS is currently flying with a number of air forces and is one of a very few civil certified OBOGS installations. PC7 MkII testing is almost completed and due for certification shortly.