Pressure breathing in high-altitude agile aircraft

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Pressure breathing with counterpressure applied to the trunk and lower limbs is employed in new-generation agile aircraft to enhance the tolerance to rapid onset and high $+Gz$ and to provide protection against hypoxia following decompression of the pressure cabin at high altitudes. The physiological requirements for the relationships between the pressures required in the mask, chest and lower-body counterpressure garments and $+Gz$ acceleration and altitude and resistance to respiration during pressure breathing, together with the extent of the coverage which should be provided by the counterpressure garments, are reviewed. The integration of these pressure breathing facilities with the molecular sieve oxygen-generating systems to be employed in the new generation of highly agile aircraft is described, and areas in which there are conflicts between the requirements of high-G protection and high-altitude protection are explored. The results of experimental studies designed to resolve these potential conflicts are described.

Keywords: Pressure breathing; High altitude.

Operational requirements have been formulated during the last decade for highly agile interceptor aircraft capable of operating at altitudes well above the ceiling of many current military aircraft of 13,716 m to 15,240 m. These highly agile aircraft will be capable of operating at $+Gz$ accelerations of up to 8–9 G sustained for many seconds and with acceleration onset rates of the order of 15–20 G/s. Considerable advances have been made in the design and performance of aircrew life support equipment to meet the high G acceleration and high-altitude environments to which the pilots of these new combat aircraft will be exposed. The logistic and operational advantages of generating breathing gas on board the aircraft, thus abolishing the need to provide liquid oxygen, has also received considerable attention. However, integration of these various gaseous life support systems to provide the optimum enhancement of the performance of the pilot presents a number of problems, some of which are considered in this paper.

Protection against high-onset-rate sustained $+G_z$ accelerations

Several studies have demonstrated that positive pressure breathing with chest counterpressure and inflation of G trousers, especially if the coverage of the latter is greater than that provided by the conventional in-service G trousers, provides enhanced tolerance of high sustained accelerations [1–4]. The rise of pressure within the chest produced by pressure breathing is transmitted to the heart and great vessels within the thorax, thereby raising the systemic arterial blood pressure. The pressure applied to the chest by the pressure waistcoat eases breathing and prevents overdistension of the lungs. The pressure applied to the abdomen and lower limbs by the extended-cover G trousers virtually prevents pooling of blood in the circulation below the heart, thereby maintaining venous return to the right side of the heart, and prevents descent or actually elevates the diaphragm, reducing the work of breathing and reducing the heart-to-head distance. Pressure breathing with G (PBG) when used with full-cover G trousers will ensure the maintenance of cerebral blood flow and prevent any impairment of mental performance or vision in the seated subject with no muscle tensing or expiratory strain (anti-G straining manoeuvre, AGSM) at 8–9 G sustained for many seconds.

The G protective system comprises an oronasal pressure demand mask, a pressure

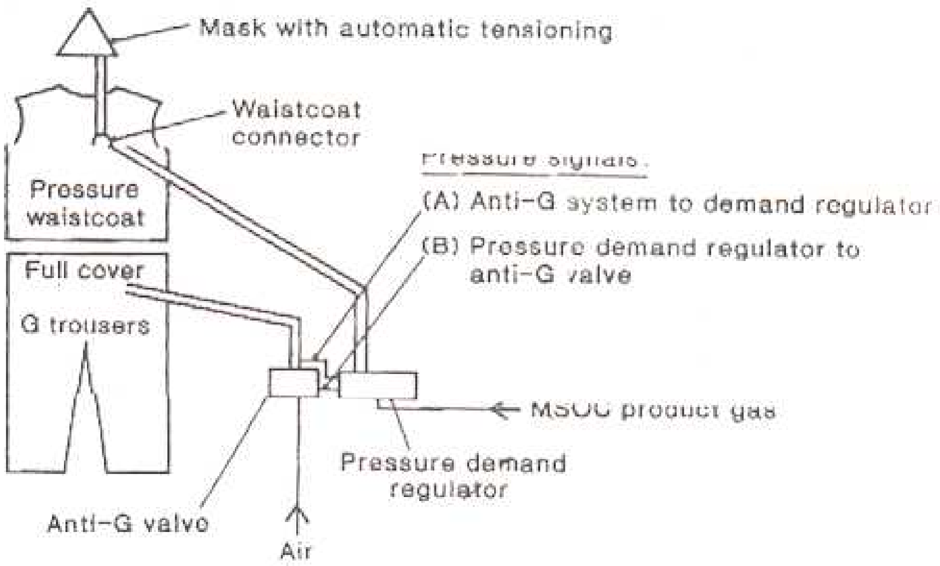

Figure 1. A schematic of the life support system for the pilot of a high-altitude agile aircraft. The aircraft equipment assembly comprises of an enhanced sealing oronasal mask and pressure waistcoat supplied by a pressure demand regulator and extended cover G trousers inflated by an anti-G valve. The demand regulator provides pressure breathing in response to the pressure delivered by the anti-G valve on exposure to G and delivers pressure breathing at altitudes above 40,000 ft. The anti-G valve inflates the G trousers during pressure breathing at altitudes in response to a pneumatic signal from the pressure demand regulator.

waist-coat covering the chest and the full-cover G trousers (Figure 1). Sealing of the oronasal mask at high breathing pressures and high G requires some method of automatically increasing the force with which the facepiece is held against the skin of the face. Most automatic mask tensioning systems developed to date employ a pneumatic bladder, placed either between the back of the pilot's head and the shell of his protective helmet, or between the rubber facepiece of the mask and its supporting exoskeleton. The bladder is connected into the delivery hose to the mask so that the force due to the rise of pressure in the mask, tending to lift the mask off the face, is counterbalanced by the force generated by the inflated bladder. The pressure waistcoat is connected into the breathing gas delivery hose between the pressure demand regulator and the oronasal mask, so that it applies a pressure to the chest wall equal to the breathing pressure. The flow of breathing gas from the supply system is controlled by a pressure demand regulator which provides the desired level of pressure breathing in response to the pressure in the connection between the anti-G valve and the G trousers (Figure 1). This arrangement ensures that the pressure demand regulator will not deliver pressure breathing unless the G trousers are inflated. Pressure breathing and exposure to high G rapidly produce unconsciousness if the trousers are not inflated. The G trousers are inflated on exposure to +Gz with cooled engine bleed air the pressure of which is controlled by a high flow capacity anti-G valve which commences delivery at 2.0 G and maintains a pressure in the G trousers which increases linearly with the applied acceleration to a pressure of 10.5 lb in^{-2} at 9 G. This pressure–G schedule is very similar to that employed in the current aircraft; the rate of inflation is, however, somewhat greater, the pressure in the G trousers

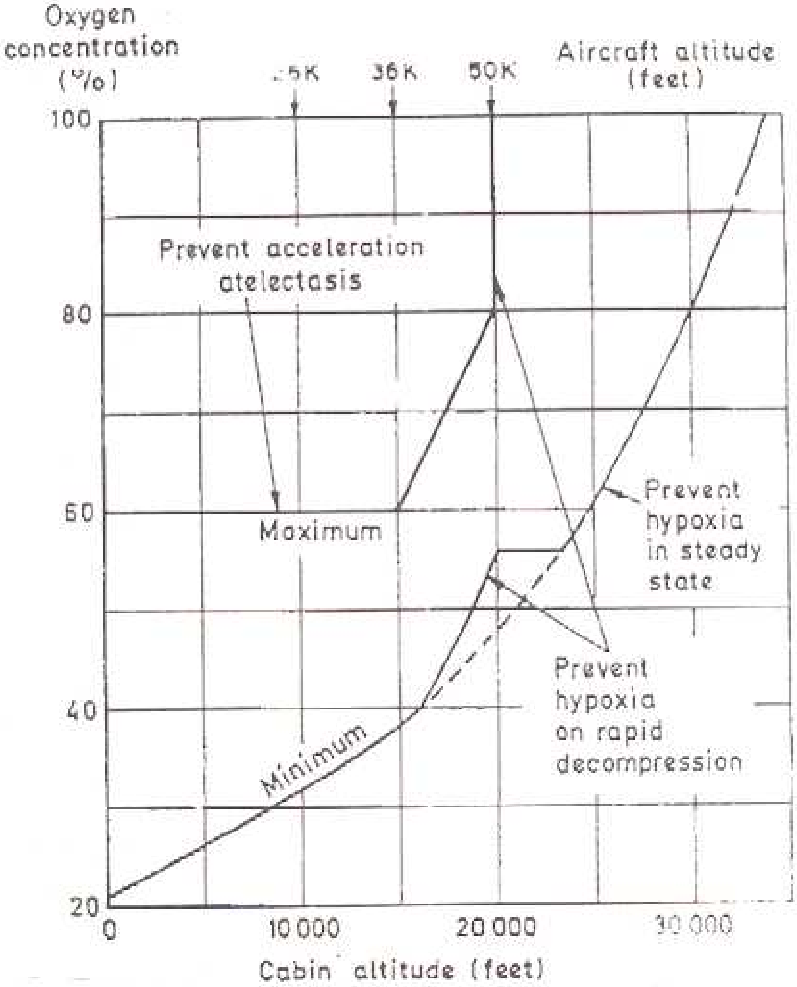

Figure 2. The physiological limits for the relationships between the concentration of oxygen in the breathing gas and cabin altitude for a high-altitude agile combat aircraft

rising to 90% of the steady-state value within 1.0 s on an instantaneous application of acceleration.

The optimum breathing pressure in such a system is 60 mmHg at 9 G. In order to avoid pressure breathing at low levels of acceleration, where it is not required, pressure breathing is commenced at 4 G. Above 4 G the breathing pressure increases linearly with acceleration at 12 mm Hg/G to 60 mm Hg at 9 G.

Extensive man-carrying centrifuge and in-flight studies performed by the RAF Institute of Aviation Medicine have demonstrated the effectiveness of such a PBG system in enhancing G tolerance to such an extent that sustained excursions to 9 G can be repeated in a sortie without impairment of pilot performance or excessive fatigue. It is also considered that this system will eliminate G-induced loss of consciousness (GLOC) in pilots operating agile aircraft at accelerations up to at least 9 G.

Protection against hypoxia at high altitudes

The primary method of protection against hypoxia and decompression sickness at altitudes is pressurization of the aircraft cabin and the delivery of breathing gas to the pilot which has a partial pressure of oxygen (pO_2) of at least 160 mmHg (inspired tracheal pO_2). The cabin pressure schedule employs a differential pressure of 5.0 lb in^{-2} at aircraft altitudes greater than 7620 m.

Several factors determine the composition of the breathing gas required by the pilot of a high-altitude agile aircraft [5, 6]. The minimum concentration of oxygen is set primarily by the requirement to maintain the alveolar pO_2 equal to that which exists when air is breathed at ground level (i.e. an alveolar pO_2 of 103 mmHg) whilst the cabin is pressurized (Figure 2). The maximum concentration of O_2 is set by the requirement to avoid lung collapse on exposure to +G accelerations. Ideally, to meet this requirement, the concentration of N_2 (together with argon) in the inspired gas should not be less than 40% if acceleration atelectasis is to be avoided. Thus, with the cabin pressurized the concentration of O_2 in the breathing gas should not exceed 60% (Figure 2). The concentration of O_2 in the inspired gas must, however, rise rapidly to 100% when the cabin altitude exceeds 8230–9144 m in the event of a decompression at high altitudes. Even if 100% O_2 is delivered to the respiratory tract within one breath following sudden decompression to altitudes greater than about 9144 m, PO_2 in the alveoar gas must be greater than 103 mmHg if significant impairment due to hypoxia is not to follow the decompression. This form of transient hypoxia can be avoided by increasing the concentration of O_2 in the gas breathed prior to the decompression, so that the alveolar pO_2 does not fall below 30 mmHg during the decompression (Figure 2).

When the cabin altitude exceeds 40,000 ft following decompression, then pressure breathing with 100% O_2 is essential if serious hypoxia is not to occur very rapidly. Very effective short-duration 'get-you-down' protection against hypoxia on exposure to altitudes above 18,288–19,812 m or even higher is provided by the use of a simple partial pressure assembly comprising an oronasal mask, a pressure waistcoat and G trousers [7]. The schedule of pressure breathing employed with this assembly is a matter of compromise between several factors, including the acceptable degree of hypoxia in a 'get-up-down' system, the maximum breathing pressure which can be tolerated using an oronasal mask to delivery pressure breathing to the respiratory tract, and the acceptable degree of impairment of the cardiovascular function. A fully proven schedule is pressure breathing rising linearly with the fall of environmental pressure from a value of 2–4 mmHg at 12,192 m to 70 mmHg at 18,288 m. The G trousers must also be inflated on exposure to altitudes above 12,192 m in order to prevent pooling of blood in the capacity vessels of the lower limbs, and to support the diaphragm through counterpressure to the abdomen. There are advantages, especially when the respiratory countrepressure is applied only to the chest, if the pressure in the G trousers is greater than the breathing pressure. The optimum relationship between the pressure in the G trousers and the breathing pressure has yet to be agreed internationally. Research conducted at the Canadian Defence and Civil Institute of Environmental Medicine [8] suggests that the pressure in the G trousers during pressure breathing at high altitudes should be four times the breathing pressure whilst that conducted at the RAF Institute of Aviation Medicine suggests that it should only be twice the breathing pressure. The pressure delivered to the G trousers in these circumstances is controlled by a pneumatic signal from the outlet of the breathing gas regulator (Figure 1). The gas breathed during pressure breathing at high altitudes should comprise 100% O_2 in order to minimize the intensity of the hypoxia associated with a given intrapulmonary pressure, which may lie between 115 and 140 mmHg absolute. Although it is proposed that some life support systems should employ product gas containing only 93–94% O_2 during pressure breathing at high altitudes, this is considered undesirable and the UK life support systems provide 100% O_2 for pressure breathing at high altitude.

On-board generation of breathing gas

The production of breathing gas on board a combat aircraft has many advantages [9]. The fully proven technique which is now in use in several combat aircraft employs beds of molecular sieve material to produce breathing gas from engine bleed air by pressure swing adsorption. The composition of the breathing gas produced by the oxygen concentrator is regulated by a closed-loop system in which the pO_2 of the product gas controls either the timing of the cycling of the beds of the concentrator or the total flow of product gas from the concentrator. Both these techniques provide close control of the concentration of O_2 in the breathing gas. A molecular sieve O_2 concentrator will cease to produce breathing gas directly if the supply of engine bleed air fails, so that a store of breathing gas is required to allow descent to below a cabin altitude of 2438–3048 m or engine re-light when an engine flame-out causes the loss of the bleed air supply. Consideration of all these various emergency situations led to the conclusion that the capacity of the back-up oxygen supply, which is nothing but compressed O_2 (1800 lb in^{-2}), should be at least 200 l NTP. This supply is mounted together with the demand regulator package on the ejection seat, so that it can also be used to prevent hypoxia on ejection at high altitudes (until man/seat separation occurs). The back-up supply of 100% O_2 is selected automatically whenever the cabin altitude exceeds 7620 m. It can also be selected manually by the pilot at any time.

The flow and pressure at which the product gas is delivered to the pilot of the aircraft is controlled by a pressure demand regulator. The breathing gas regulator provides safety pressure at all altitudes up to 12,192 m, pressure breathing at altitudes above 12,192 m and pressure breathing with G. The regulator is also fitted with a press-to-test facility which allows the seal of the mask and the security of the connections to be tested during pre-flight cockpit checks. The outlet of the regulator is fitted with a dump valve which is compensated to its pressure control chamber. This dump valve limits the mask hose pressure rise with hose pumping, on rapid decompression and in the presence of a small leak through the demand valve of the regulator.

Impedance to breathing

A low impedance to respiration is an essential feature of the integrated gaseous life support system for a high-altitude agile aircraft. The design of the O_2 concentrator system delivering breathing gas to the demand regulator, of the breathing gas regulator, of the hoses and connectors downstream of the demand regulator and the aircrew mask must be such that the resistance to the flow of breathing gas is minimized. By paying attention to the flow capacity of the O_2 concentrator and demand regulator and the seat mounting of the regulator, it is possible to ensure that the impedance to respiration does not exceed the values specified in Table 1, both during normal operation and during pressure breathing with +G acceleration and at high altitudes [6].

Table 1. Maximum acceptable impedance to respiration imposed by integrated high-G, high-altitude protect assembly

Peak inspiratory and expiratory flows (Litre (ATPD) min^{-1})	Maximum swing of mask pressure during respiratory cycle (inch water gauge)
30	2.0
90	3.0
150	7.0
200	12.0

Physiological hazards arising in life support systems for high-altitude agile aircraft

Two potential hazards have been identified during the development of integrated life support systems providing pressure breathing with G and at high altitudes. The first arises from the presence of product gas between the back-up supply of 100% O_2 and the mask during and following a rapid decompression. The second arises from the possibility of a rapid decompression of the cabin of the aircraft occurring whilst pressure breathing with G is operative.

Hypoxia on rapid decompression. Although the concentration of O_2 in the breathing gas is adequate to prevent the PO_2 of the alveolar gas falling below 30 mmHg on rapid decompression (Figure 2) and 100% O_2 from the back-up oxygen supply is selected immediately as the cabin altitude exceeds 7620 m, the capacity of the pipework between the regulator and the mask may so delay the arrival of 100% O_2 to the mask cavity that serious hypoxia results. Ideally, the maximum volume of gas which has to be inspired following a sudden decompression before the concentration of O_2 in it rises to greater than 99% should not exceed 600 ml (ATPD). Rapid decompressions of a prototype integrated life support system in which this volume was 1.2 l induced unacceptable hypoxia [10]. The back-up supply of 100% O_2 must be delivered directly to the inlet of the breathing gas regulator and the capacity of the pipework from the regulator to the mask should be minimized. The very large additional volume of breathing gas containing 40 50% N_2 which would be introduced when a rapid decompression occurs with the pressure waistcoat inflated during pressure breathing induced by a high-G manœuvre would certainly produce unconsciousness due to hypoxia. A non-return valve is required in the connection between the breathing gas delivery hose and the bladder of the pressure waistcost to prevent the gas in the bladder passing into the respiratory tract. The presence of this non-return valve necessitates the provision of a compensated dump valve whereby gas in the waistcoat can be vented directly to the environment during inspiration.

Venting of lung gas on rapid decompression. Rapid decompression of the cabin when using a conventional pressure demand system with a well-sealing oronasal mask can lead to lung damage by overexpansion of the lungs as the compensated outlet valve of the mask is held shut by the differential pressure created in the hose between the demand regulator and the inlet valve of the mask. This hazard is overcome in modern demand systems by fitting a compensated dump valve at the outlet of the breathing gas regulator, which vents the gas trapped in the hose between the regulator and the mask, so that the rise of pressure in the hose on a rapid decompression is minimized and the expanding gas from the lungs can escape through the outlet valve of the mask. The current requirement for a pressure demand regulator mask system is that the mask cavity pressure shall not exceed 40 mmHg on a rapid decompression in 0.1 s [6]. The addition of the gas trapped in the pressure waistcoat when the latter is inflated to provide pressure breathing with G increases greatly the pressure which is generated in the system. A rapid decompression whilst executing a high-G manoeuvre so that the pressure waistcost is already inflated to a pressure of 50–60 mmHg – a realistic scenario in air combat – will raise the pressure in the mask and the pressure waistcoat to 150–200 mmHg above that in the cabin. The inflated waistcoat increases the volume of the gas trapped between the outlet of the regulator and the mask from about 400 ml to 7–9 l. The size of the compensated dump valve at the outlet of the breathing regulator would have to be increased manyfold to allow the gas trapped in such a system to escape during a rapid decompression. The solution to this potential hazard is to add a non-return valve and a compensated dump valve to the connection into the pressure waistcoat, which allows the gas trapped in the waistcost to escape to the cabin. Rapid decompression of such systems has demonstrated the effectiveness of this arrangement in reducing markedly the pressures generated in the mask and pressure waistcoast. Not only does this arrangement reduce the peak pressure in the mask but the difference between the pressures in the mask and the pressure waistcoat does not exceed 5–10 mmHg throughout a rapid decompression in 0.1 s. The presence of this counterpressure to the chest, together with the pressure in the abdominal bladder of the G trousers, will prevent distension of the lungs by a rapid decompression when pressure breathing with G is operative.

Summary

Pressure breathing using the appropriate counterpressure to the trunk and lower limbs enhances greatly the tolerance of a pilot to high sustained +G accelerations and provides good protection against hypoxia on exposure to altitudes above 40,000 ft. The design of a single integrated assembly which will provide this high-G and high-altitude protection to the pilot of an agile aircraft which is required to operate at high altitude gives rise to a number of potentially serious interactions which require specific attention. The avoidance of serious hypoxia and lung damage on rapid decompression at high altitudes have been considered in this paper.

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