DEF STAN 00-970 NOTICE OF PROPOSED AMENDMENT (Def Stan 00-970-NPA)

TITLE OF PROPOSAL: Review of Part 13 Leaflet 3

Stage of Amendment: Issue 1

Def Stan 00-970 NPA Serial No:	2014-004		
Unsatisfactory Report Serial No:	*N/A*		
MAA Originator:	C2	R A Bennett-Jones	MAA-Cert-ADS1a

Affected Part: (including paragraphs) Part 13 Section 2 Leaflet 3

Cross-reference to other relevant amendment proposals or documents: Content Reporting Form 2014-001

ADS Point of Contact details

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Part 1 (for issue to User Community)

INTRODUCTION *(Not more than 250 words)*

Enter here a brief explanation of why NPA is being issued, i.e. what does the amendment hope to achieve, by when and how:

The requirements for Oxygen within Def Stan 00-970 have been reviewed as a result of the drafting of Part 5 Large Aircraft. This led to the raising of a content reporting form by RAFCAM to amend Part 13 Leaflet 3.
This NPA is as a result of the CRF from RAFCAM.

The new text will be clearly identifiable within Annex A.

SUMMARY OF PROPOSED AMENDMENT

Change: *See Annex A*

Impact Assessment:

Objective: Clarification of the requirements

Risk Assessment: The impact of not incorporating the recommended changes is the possibility of misinterpretation of the requirement

Courses of Action.

1. ***Do nothing.*** The option to do nothing is not desirable for the following reason. Not incorporating the changes will result in confusion in compliance between Part 5 and Part 13.

2. ***Partial Amendment.*** Due to the minor nature of the change partial amendment is not considered.

3. ***Full Amendment.*** There is no reason that full implementation of all the changes should not be completely feasible. The changes will remove the confusion in the work required to comply with the 00-970 Clauses. Retrospective mandating is not considered necessary.

Preferred Course of Action. Full Amendment.

Costs and Benefits:

1. ***Do nothing.*** There is no benefit of the do nothing option, which could result in increased cost to the department in confirming compliance with confusing requirements within Def Stan 00-970.
2. ***Partial Amendment.*** *No Benefit*
3. ***Full Amendment.*** Full amendment will clarify Def Stan 00-970 Part 5 and Part 13 requirements for Oxygen and will reduce confusion, resulting in improved overall compliance with the requirement. The changes proposed here represent current practice and would have no or little economic impact.

Consultation period ends: 20/Jun/2014

The consultation period for this proposed amendment ends on the stated date. Please send your feedback via email to MAA-Cert-ADSGroup@mod.uk.

Part 2 (for MAA internal use)

Log of Comments: (to be completed once the consultation period has ended).

Comment reference	Date	From (name)	Post	Précis or Topic of Comment	MAA Response

Recap of Proposal: *A short summary of the proposal amendment including what changes were incorporated following the consultation period.*

Recommendation: *This section will be completed once all the comments have been received. The recommendation is for the relevant Head of Division to approve the proposal.*

Approval: *This section will detail exactly what has been approved and by whom, and confirm the date for the amendment to be incorporated as well as the date the NPA should be reviewed to determine what the effects of the amendment were in terms of meeting the objective of the change, if there were any unintended consequences and establishing whether the estimated costs were correct.*

Accepted changes will be authorised at the following levels:

- Changes requiring retrospective mandating: 2 *
- Changes not requiring retrospective mandating but having a significant engineering impact: 1* Head of Cert.
- Changes not requiring retrospective mandating but having a Minor engineering impact: OF 4 Deputy Head of Cert.
- Changes deemed as administrational only: Head of S and ADS.

Approved by:

Signature:

Name:

Rank/Grade:

Post:

Date signed:

Date for amendment to be incorporated: 05 January 2014

Part 3 - NOTIFICATION OF AUTHORIZED AMENDMENT (Def Stan 00-970 NAA)

Document Part:	***Part 13***	Sub-Part:	***Section 2 Leaflet 3***

Unsatisfactory Report Reference:	*2014-001*	NPA Reference:	***2014-004***

Originator:	*R A Bennett-Jones*	Date:	

Amendment to be Incorporated on	

APPROVAL

This Def Stan 00-970 NPA has been approved by ….. on behalf of DG MAA

INCORPORATION

The amendment will be incorporated in issue XX …

Signed (IAW with part 2).

for DG MAA

Annex A

Current Text Part 13

LEAFLET 3

OXYGEN SYSTEMS
PHYSIOLOGICAL REQUIREMENTS FOR OXYGEN SYSTEMS

1 Introduction

1.1 This leaflet describes the basis of the physiological requirements for breathing systems which are fitted to aircraft primarily to provide individual protection against hypoxia for aircrew and passengers. Breathing equipment is also employed to provide protection against the inhalation of toxic gases and fumes which may arise in the cabin environment and of airborne nuclear, biological and chemical (NBC) warfare agents. Recently the delivery of positive pressure breathing has been adopted as a means of enhancing aircrew tolerance of high sustained +Gz accelerations (pressure breathing with G, PBG). Breathing equipment may, by the composition of the gases delivered to the respiratory tract and/or the associated impedance to breathing induce undesirable or indeed unacceptable physiological and/or performance disturbances in the individual.

1.2 The present-day physiological requirements for the performance of aircraft breathing systems have been evolved principally over the last forty years. They represent practical compromises between the physiological ideal that the equipment should produce no disturbance whatsoever to the user, the performance of available designs and the operational and logistic requirements of simplicity, reliability, low maintenance and low financial cost. They are based upon laboratory and airborne research and operational experience. As the requirements are compromises they may vary with the application. Thus the degree of hypoxia which is acceptable in seated passengers following decompression of the cabin of an aircraft at high altitude differs markedly from that which is acceptable in the pilot of high performance combat aircraft during flight with the cabin pressurised.

1.3 The design and operation of an aircraft breathing system must be very closely related to the breathing requirements of the wearer. The three major aspects of these are the respiratory flow demands, the pressure at the entrance to the respiratory tract (nose and mouth) and the composition of the gas which is delivered to the respiratory tract. The physiologically acceptable values of these breathing requirements are addressed in this leaflet together with the other physiological factors which affect the performance of aircraft breathing systems.

2 Respiration in Flight

2.1 The ranges of instantaneous and average flow rates which can be demanded by fit adults are extremely large. Thus the peak inspiratory flow rate can vary from 0.4 - 0.5 L (BTPS) s-1 at rest to 10 L (BTPS) s-1 in maximum exercise, and the mean inspired pulmonary ventilation from 6 L (BTPS) min-1 at rest to 150 L (BTPS) min-1 in maximal exercise. Whilst it is self-evident that aircrew will not perform maximal exercise in flight a pilot who climbs into the cockpit of his aircraft after running may well have a very high respiratory demand. Knowledge of the pulmonary ventilation (average inspiratory or expiratory flow) and the instantaneous respiratory flow rates demanded by aircrew (and passengers) in flight and on the ground is essential for the specification of the performance required of an aircraft breathing system. Thus the pulmonary ventilation which occurs under various conditions of flight will determine the size of the main, back-up and emergency stores of oxygen required in an aircraft. Knowledge of the ranges of pulmonary ventilation which may be demanded by aircrew over relatively short periods of flight [30 seconds or so] is required for the specification of the performance of molecular sieve oxygen concentrator systems. Finally the impedance to respiration imposed by any breathing system is a function of the instantaneous inspiratory and expiratory flow rates created by the wearer.

Effect of Altitude

2.2 The gases in the lungs are always saturated with water vapour at body temperature (37°C) so that the partial pressure of water (PH2o) in the alveolar gas is always 47 mmHg. These conditions of a temperature of 37°C and a PH2o of 47 mmHg are termed body temperature, pressure and saturated with water vapour (BTPS). Thus as a dry gas at ambient pressure and temperature (ATPD) enters the lungs, it expands, not only due to the rise in temperature, but also due to the addition of water vapour. Whilst the increase in volume due to a change of temperature from the standard temperature of NTPD conditions (15°C) to 37°C of 7.6% is independent of changes in ambient pressure, the increase in the volume of the gas due to the PH2o rising from 0 to 47 mmHg varies with altitude from 6.6% at ground level, to 14.1% at 18,000 feet and 50% at 40,000 feet. Whilst the dependence of the relationship between gas volumes at ATPD and BTPS conditions upon ambient pressure (altitude) is of great importance in calculating the size of oxygen stores this effect is normally neglected when considering instantaneous respiratory flow rates over the normal range of cabin altitudes. Indeed specifications of instantaneous flow rates are by convention considered to be unaffected by altitude and are stated as flow rates of dry gas at 15°C and at the absolute pressure within the respiratory tract (mask cavity) (ATPD). These conventions are followed in the ASCC Standards and NATO STANAGS and in Section 1 Clause 1.4

2.3 The level of pulmonary ventilation of an individual in the absence of hypoxia and emotional disturbances is very closely related to the rate of production of carbon dioxide by the body, which in turn is very closely related to the physical activity of the individual. Indeed as a first approximation pulmonary ventilation is adjusted in relation to the rate of production of carbon dioxide to maintain a constant partial pressure of carbon dioxide (Pco2) in the alveolar gas and the arterial blood. Thus at a constant level of activity (rate of production of carbon dioxide) the pulmonary ventilation expressed as volume under BTPS conditions is unaffected by ascent to altitude, provided that the concentration of oxygen in the inspired gas is raised in order to prevent any hypoxia (see below).

Average Pulmonary Ventilation

2.4 The maximum average pulmonary ventilation is the essential component of any calculation of the quantity of gas required to supply aircrew using a demand type of flow regulated breathing system. The value used for the latter must take into account the effects of various stages of a sortie and of types of flight on pulmonary ventilation, and the variation in the individual responses to each condition. Extensive flight trials in the UK in the early 1960s led to the adoption of the maximum [to include 97% of occurrences] pulmonary ventilations, averaged over the whole sortie of the crews of combat aircraft presented in Table 1. Increasing the number of crew will reduce the mean pulmonary ventilation per individual as it is very unlikely that the pulmonary ventilations of several crew members will be at the maximum value measured for a single crew member. Flight trials conducted in fighter and bomber aircraft in the early 1960s formed the basis of the values presented for multiple crews in Table 1. These values together with the air dilution characteristics of the MK17, 20 and 21 series of pressure demand regulators form the basis of the oxygen requirements for aircrew in Section 1.4. Measurements of pulmonary ventilation in mock air-to-air combat in a Hunter T7 aircraft yielded a mean value for 18 pilots of 18.8 L (BTPS)min-1 with a maximum average value (to include 97% of all observations) of 24L(BTPS)min-1.

Pulmonary Ventilation of Aircrew operating combat aircraft averaged over a sortie [values to include 97% of occurrences]

Number of Seats in aircraft	Average Pulmonary Ventilation (L (BTPS) min-1)
1	21.8
2 or 3	18.6
4 or more	16.2

Table 1 - Pulmonary Ventilation of Aircrew operating combat aircraft

2.5 An alternative approach is that presented in US Military Standard MIL-D-19326H, Oct 78 which employs baseline pulmonary ventilations for the calculation of the ventilation averaged over the whole sortie of 18.0 L (BTPS) min-1 for a single pilot and 16.5 L (BTPS) min-1 for each of a two man crew. The MIL standard increases the baseline pulmonary ventilation by 75% when the aircraft is engaged in aerial combat and by 25% when terrain following. Calculations of maximum average pulmonary ventilations for comparable fighter and bomber sorties using the MIL-D-19326H approach yield values in reasonable agreement with the values for pulmonary ventilation presented in Table 1.

2.6 It should be emphasised that the values for maximum average pulmonary ventilation over complete sorties presented in Table 1 should be used with caution in circumstances outside those in which the information on which they are based was collected. Although estimates of the quantity of oxygen required in aircraft storage systems in UK military aircraft have been based upon these values for pulmonary ventilation since the early 1960s the adoption of standard sizes of LOX converters in the mid-1960s led in general to the capacity of the oxygen store being greater than that required by the values presented in Table 1. This greater margin of oxygen supply would tend to mask in service any underestimate of the quantity of oxygen required based on the values in Table 1.

Minimum and Maximum Pulmonary Ventilation

2.7 The pulmonary ventilation of an aircrew member may vary markedly with time during a flight. Thus pulmonary ventilation is typically raised during the stress of take-off and landing. It is raised by flight at low level and when performing the anti-G straining manoeuvre and by air combat. The minimum and maximum levels of pulmonary ventilation which may occur in flight are of importance to certain aspects of the design of breathing systems, such as the performance of the injector form of air dilution mechanism employed in many demand regulators and the concentration of oxygen in the product gas provided by a molecular sieve oxygen concentrator. In this context the relevant value of the pulmonary ventilation is typically that averaged over a period of 30 seconds or longer. The minimum pulmonary ventilation which will be demanded by a pilot during undisturbed straight and level flight or by a seated passenger is very similar to the minimum seen in subjects seated at rest on the ground i.e. 6.0 L (BTPS)min-1. Thus the value for the minimum pulmonary ventilation to be met by aircraft breathing systems used by either aircrew or passengers adopted in current national and international standards is **5.0 L (ATPD) min-1**.

2.8 The few studies which have been made of maximum pulmonary ventilation in flight in pilots performing simulated aerial combat and other manoeuvres have yielded values between 51 and 60 L(BTPS) min-1 for the maximum pulmonary ventilation maintained for 30 seconds or longer. Values higher than 40 L (BTPS) min-1 were recorded on 1-2% of occasions. The standard adopted by the ASCC and NATO nations for the maximum pulmonary ventilation which can be sustained in flight for 30s or more is **50 L (ATPD) min-1**. It is unlikely that the flight deck crew of transport aircraft would exhibit pulmonary ventilations as high as 50 L(ATPD) min-1, whilst seated in flight. A realistic value for the maximum pulmonary ventilation to be sustained by these aircrew for 30 seconds or longer is 40 L(ATPD)min-1. The maximum pulmonary ventilation demanded by flight deck crew when moving out of their seats may well, however, approach 50 L(ATPD) min-1. A sustained pulmonary ventilation of 50 L(ATPD) min-1 would be demanded by an aircrew member fighting an in flight fire. The pulmonary ventilations of seated passengers will under normal flight conditions vary between 5 and 20 L(ATPD) min-1, depending upon their level of activity. The emotional disturbances, such as fear, which may be engendered by decompression of the cabin can raise the pulmonary ventilation of passengers above this range. Present UK Civil Aviation Authority and US Federal Aviation Agency requirements for passenger breathing equipment specify a maximum sustained pulmonary ventilation of **30 L (BTPS) min-1**.

Instantaneous Respiratory Flow Rates

2.9 The instantaneous rates of flow of gas into and out of the respiratory system is one of the principal factors which determine the magnitude of the changes in mask pressure imposed by a breathing gas delivery system, the other being the pressure-flow characteristics of the breathing equipment itself. There is considerable variation in respiratory flow patterns between individuals, especially when breathing whilst at rest. Typically, the breathing frequency is 15 breaths a minute with each inspiration occupying 1.6 seconds and each expiration lasting 2.4 s. During inspiration the instantaneous flow rate typically rises rapidly to a maximum after 0.5 seconds and then falls at a slower rate to zero. Expiration usually follows the end of inspiration without a break. The instantaneous flow rate in expiration rises to reach a maximum which is somewhat less than the maximum attained in inspiration. The flow rate then declines slowly to reach zero at the end of this phase of the cycle. There is frequently a pause between the end of expiration and the commencement of the next inspiration. Of particular significance to the design of aircraft breathing systems are the maximum (peak) inspiratory and expiratory flow rates which occur during the respiratory cycle. Although for some purposes the instantaneous respiratory flow can be simulated by a sine wave (when the peak flow rate equals 3.14 times the pulmonary ventilation) the peak inspiratory flow rate at rest is typically 3.2-3.8 times the pulmonary ventilation whilst the peak expiratory flow rate is about 2.7 - 3.0 times the pulmonary ventilation. Respiratory flow patterns tend to become more regular as the pulmonary ventilation is increased by physical exercise. Inspiratory and expiratory times become more equal as do peak inspiratory and expiratory flow rates. Moderate increases of pulmonary ventilation produced by physical exercise typically occur by an increase in the size of individual breaths (i.e. increase of tidal volume) rather than an increase in the frequency of breathing. When the respiratory frequency increases it principally occurs by a shortening of the duration of expiration; the duration of inspiration only decreases slightly with increasing frequency of breathing.

2.10 Respiratory flow patterns are modified by numerous factors ranging from exercise, speech and swallowing to the imposition of external resistance to breathing (see paragraph 3.1) and pressure breathing. Of particular relevance to the requirements for aircraft breathing systems are the changes produced by speech and the anti-G straining manoeuvre (AGSM). The duration of inspiration is markedly reduced by speech and since there are usually only minor changes in the tidal volume the peak inspiratory flow rate is increased to 5 to 10 times the pulmonary ventilation. The expiratory flow is modulated during speech and the maximum flow rate is less than that during breathing at the same level without speech. The voluntary breathing manoeuvres involved in the AGSM greatly reduce the duration of inspiration and expiration. The breathing cycle is typically completed in 1.0-1.5 seconds and the peak inspiratory and expiratory flow rates are increased to between 7 and 15 times the pulmonary ventilation. Pressure breathing without counter-pressure to the chest also produces marked changes in respiratory flow patterns with an increase in peak inspiratory flow rate and expiration becoming prolonged with a relatively constant expiratory flow rate. The application of full counter-pressure to the chest tends to restore the breathing flow patterns to those seen in the absence of pressure breathing. The flow patterns during pressure breathing with +Gz acceleration with counter-pressure applied to the chest and abdomen are similar to those which occur in light exercise provided that the individual does not perform any respiratory straining manoeuvre.

2.11 The specifications of the maximum peak flow rates to be met by aircraft breathing systems are based principally upon the breathing patterns of aircrew recorded in flight. These have shown that the peak inspiratory and expiratory flow rates of pilots operating high performance combat aircraft can be as high as 5L(ATPD) s-1. Analysis of the frequency distributions of peak flow rates recorded in several in flight studies has shown that the occurrence of peak flow rates in excess of 3.3L (ATPD) s-1 is 2.5%. Present ASCC and NATO specifications require that breathing systems must be capable to meeting peak inspiratory and expiratory flow rates of at least 3.3 L (ATPD) s-1. Ideally aircraft breathing systems should be capable of meeting peak flow rates of up to 4.2L (ATPD) s-1. Since speech at moderate levels of pulmonary ventilation (20 L(ATPD) min-1) will produce peak inspiratory flow rates of 2.5-3.3 L(ATPD) s-1 breathing systems designed for use in multi-crew aircraft, including transport aircraft, must also be capable of meeting peak inspiratory flow rates of 3.3 L(ATPD) s-1.

2.12 In pressure demand breathing systems, the impedance to respiration imposed by the system is a function not only of the instantaneous respiratory flow rate, but also the rate of change of flow rate. The rates of change of flow rate which occur during breathing are related to the nature of the respiratory manoeuvre e.g. quiet breathing, speech, AGSM, pressure breathing and, to a limited extent, to the peak respiratory flow rate. Thus speech at rest increases the median rate of increase and decrease of inspiratory flow rate during quiet breathing from 1.6 L s-2 to 18 L s-2. In practice, the highest rates of change of flow occur in speech and whilst performing the AGSM. The minimum rates of change of inspiratory and expiratory flow rates specified by current ASCC and NATO requirements for aircrew breathing systems are 10 L(ATPD) s-2 at a peak flow rate of 1.5 L(ATPD) s-1 increasing to 20 L(ATPD) s-2 at a peak flow rate of 3.3 L(ATPD) s-1. These rates of change of flow rate define the rate of change between 0 flow and 90% of the relevant peak flow rate.

2.13 As already discussed (paragraph 2.4) it is unlikely that the breathing patterns of the members of two crew or multi-crew aircraft will coincide exactly in time. Monte Carlo simulation of the inspiratory demands of two crew members suggests that 95% of all instantaneous peak demand flow rates can be met by a breathing system which will provide 70% of the flow demanded when the two crew members are breathing exactly in phase. An in-flight study in which the inspiratory flow patterns of the two crew of a two seat combat were recorded during level flight, high G aerobatics and simulated combat manoeuvring, showed that the beginning of inspiration occurred simultaneously in the two pilots in less than 1% of 5,000 breaths. The present UK standard requires that a breathing system for two crew members provides 85% of the peak inspiratory flow rate which could be demanded by both crew members breathing exactly in phase i.e. 5.6 L(ATPD) s-1.

3 Resistance to Respiration

Effects of external resistance

3.1 Excessive external resistance to breathing can give rise to breathing discomfort, fatigue of the respiratory muscles and to changes in pulmonary ventilation, generally hypoventilation but on occasions hyperventilation. Excessive resistance also impairs speech and the ability to perform the ASGM. Finally, changes in the mean pressure in the lungs induced by external resistances can disturb the cardiovascular system and the distribution of body fluids. Many laboratory based studies of the effects of adding external impedances to breathing have employed resistances which had a linear relationship between pressure drop and flow rate. Such studies showed that subjective discomfort occurred when resistances with a pressure drop greater than 0.5 kPa at a flow rate of 1.4 L (ATPD) s-1 were imposed in inspiration and expiration together. Other studies in which the additional work of breathing produced by a variety of levels of external resistance was measured suggests that the limit of breathing comfort is reached when the external work exceeds [0.5 + 0.02 x (pulmonary ventilation)] Joule per litre of pulmonary ventilation.

3.2 In practice the resistance to respiration imposed by an aircraft breathing system is defined in terms of the relationships between the pressure in the cavity of the mask and the corresponding respiratory demands. It is generally most appropriate to relate the minimum and maximum mask pressures during the respiratory cycle to the corresponding peak inspiratory and expiratory flow rates demanded by the wearer. It is normal practice to describe the resistance imposed by aircrew breathing equipment in terms of the total change of pressure in the mask cavity [the pressure swing] and the minimum and maximum mask pressures which are produced by equal inspiratory and expiratory flow rates. The pressure in the mask cavity meaned over the whole of the respiratory cycle is also a valuable expression of the performance of a breathing gas system, as this quantity determines in part the stresses imposed on the heart and circulation by the equipment.

Total change of mask pressure

3.3 The total change (swing) of pressure in the mask cavity during the respiratory cycle (i.e. the difference between the minimum and maximum mask cavity pressures) should be as low as possible. The greater the swing, the greater is the sensation of resistance to breathing and the greater is the likelihood of incidents of hyperventilation, particularly in situations of high mental workload. The current standard for the maximum permissible change of mask cavity pressure during the respiratory cycle (with equal peak inspiratory and expiratory flow rates) is presented in Table
2. This standard ensures breathing comfort at pulmonary ventilations between 5 and 50 L (ATPD) min-1. Although internal airway resistance is reduced at altitude, the effect on the total work of breathing is relatively small and it is present practice to require the resistance to breathing imposed by an aircrew breathing system to be within the same maximum limits at all altitudes from ground level to 38,000 feet, above which altitude pressure breathing is operative.

Peak Inspiratory and Expiratory Flow Rates (L (ATPD) s-1)	Maximum Acceptable Change of Mask Cavity Pressure during the Respiratory Cycle (kPa)
0.5	0.5
1.5	0.85
2.5	1.75
3.3	3.0

Table 2 - The Maximum Acceptable Change of Pressure in the Mask Cavity during the Respiratory Cycle at Altitudes between Ground Level and 38,000 feet.

Safety Pressure

3.4 The design of an oronasal mask and its suspension system should be such that a good seal between the edge of the mask and the face is maintained under all conditions of flight. The standard of this seal should be such that the inboard leakage of ambient air into the mask cavity does not exceed 5% of the pulmonary ventilation when the mean pressure in the mask cavity is between 0 and 1 kPa less than that of the environment. There are, however, situations in which this level of sealing of the mask to the face may not be achieved. Indeed a serious disadvantage of suction demand breathing systems in practice is that hypoxia can occur at altitude due to the inspiration of air through a leak between the mask and the face. Safety pressure which is the maintenance of the pressure in the mask cavity during inspiration at a value greater than that of the environment is widely employed in aircrew breathing systems to prevent the flow of environmental gas into the mask when there is a failure of the seal of the mask to the face. The ingress of air, toxic fumes or NBC warfare agents through a leak between the mask and the face could have serious consequences. As long as the pressure in the mask cavity remains greater than that of the environment, then a failure of the seal of the mask to the face will result in a flow of breathing gas from the mask to the environment thus preventing the contamination of the breathing gas in the mask by air or toxic materials in the air. Although it is desirable that safety pressure is maintained in the mask cavity even at high inspiratory flow rates and in the presence of large leaks, the pressure-flow characteristics of most breathing gas delivery systems, in which the mask pressure falls with increasing flow, and the compensation of the expiratory valve, make this goal difficult, if not impossible, to meet. In such systems, a high safety pressure will be associated with a high resistance to expiration. A mean pressure in the mask cavity of +0.5kPa will, however, minimise the total work of breathing and increase breathing comfort.

3.5 The fraction of the inspired gas which enters a mask through a typical mask leak in a suction demand system is greatest at low inspiratory flow rates. The ratio of flow through the leak to total inspiratory flow falls rapidly as the latter rises. The presence of safety pressure is therefore most important during quiet breathing. It is thus possible to strike a compromise between the maximum inspiratory flow rate at which safety pressure is required to be present and the rise in mask expiratory pressure produced by the safety pressure. The present standard requires safety pressure to be present in aircrew breathing systems at inspiratory flows of up to at least 1.2 L(ATPD) s-1 and limits the maximum mask pressures during expiration to the values presented in Table 3 (Section B - safety pressure present). The minimum mask pressures allowed when safety pressure is present are also presented in Table 3. These limits to the peak mask pressures when safety pressure is present ensure that the effects of the associated increase of mean lung pressure of +0.25 to +0.5 kPa upon the circulation and distribution of body fluids are minimal and acceptable for many hours.

Peak Inspiratory and Expiratory Flow Rates (litre (ATPD) s-1)	Acceptable Mask Cavity Pressures (kPa) Minimum	Maximum
A. Safety Pressure Absent		
0.5	-0.38	+0.38
1.5	-0.55	+0.65
2.5	-1.12	+1.00
3.3	-1.90	+1.50
B. Safety Pressure Present		
0.5	+0.02	+0.75
1.5	-0.20	+0.95
2.5	-0.90	+1.25
3.3	-1.75	+1.65

Table 3 - The Minimum and Maximum Acceptable Mask Cavity Pressures during the Respiratory Cycle at Altitudes between Ground Level and 38,000 feet.

3.6 In some aircraft breathing systems safety pressure is only operative at altitudes above either 10,000-12,000 feet or 30,000 feet. Below these altitudes, gas only flows from the regulator when the pressure in the mask is reduced below that of the environment. The reduction of mask pressure which occurs during inspiration in these circumstances should not give rise to the sensation of excessive inspiratory resistance. The suction in the mask cavity is not to exceed the values specified in Table 3 for the absence of safety pressure (section A). The maximum mask pressures which occur when safety pressure is not operative should be such that there is no sensation of excessive expiratory resistance.
The maximum acceptable values are specified in Table 3 (Section A - safety pressure absent).

Further Increases of Mask Pressure

3.7 In use, certain routine and emergency conditions tend to raise the pressure in the mask cavity above the values seen during breathing in the steady state. Thus, in a typical pressure demand system in which the outlet valve of the mask is compensated to the pressure in the inlet hose of the mask, head movement increases the pressure in the mask hose and hence the resistance to expiration and similarly a rise of mask hose pressure produced by a rapid ascent also increases expiratory resistance. In order to maintain breathing comfort, the rise of mask cavity pressure induced by realistic head movements or by the maximum rate of ascent of cabin altitude (with the cabin pressurised) is not to exceed 0.25 kPa. A continuous flow failure of the demand valve in a conventional compensated mask outlet valve system will result in a continuous rise of mask pressure. If the flow through the demand valve is relatively low, the wearer will experience expiratory difficulty. A high continuous flow will produce a rapid rise of mask and lung pressures, provided that the seal of the mask to the face is maintained. Inflation of the lungs to an intrapulmonary pressure of 10.7-13.3 kPag will, if the expiratory muscles are relaxed, result in over-distension of the lung tissue, rupture of the walls of air sacs and the passage of gas into the lung tissue, into the tissues within the chest and neck, into the pleural space (producing lung collapse) and most seriously into the ruptured pulmonary capillaries, allowing bubbles of gas into the heart and arterial vessels with a high probability of blocking arteries supplying parts of the brain which may cause unconsciousness and death. The rise of mask pressure produced by a high continuous flow failure of a demand valve must not exceed 5.5 kPa.

Venting of lungs on rapid decompression

3.8 Rapid decompression of the pressure cabin of an aircraft produces an almost equally rapid expansion of the gases in the lungs and airways and can produce over-inflation of the lungs with damage to the lung tissue with the consequences discussed in paragraph 3.7. The incidence and severity of the damage to the lungs produced by rapid decompression are determined primarily by the ratio of cabin pressure before the decompression to that after the decompression, the speed of the decompression (the reciprocal of the time constant of the decompression), the degree of opening the glottis (the orifice between the vocal chords) and the resistance to the flow of gas from the respiratory tract imposed by the breathing equipment. The breathing equipment worn by aircrew should allow free venting of the expanding gases from the lungs in these circumstances. The peak pressure difference between the gas in the lungs and the environmental pressure produced by a rapid decompression should not exceed the 10.6 - 13.3 kPag required to produce pulmonary damage by over-inflation of the relaxed chest. Present standards for aircrew breathing equipment require that the mask pressure on a rapid decompression to a final altitude of 38,000 feet (above this altitude pressure breathing is operative) in 0.1 seconds shall not exceed 5.5 kPag. This limit is somewhat arbitrary. It is one half of the intrapulmonary pressure required to damage the lungs by over-distension of the relaxed chest. There is recent experimental evidence that short duration (<50 ms) peak mask pressures of up to 13.3 kPag on rapid decompression over a 35 kPa pressure change in 0.2 seconds will not cause lung damage. The probability of lung damage on rapid decompression is reduced if over-distension of the lungs is prevented by the application of counter pressure to the chest wall and abdomen during the decompression.

Oscillatory activity
3.9 Aircrew breathing systems can exhibit oscillatory activity which produces oscillations of pressure in the mask, usually during inspiration. Such oscillations of mask pressure, particularly if they are of sufficient amplitude, are subjectively disturbing, may induce hyperventilation and can interfere with communication. The incidence, amplitude and frequency of these oscillations are determined by the oscillatory mechanics of the breathing equipment, by the impedance of the respiratory tract [when present, oscillatory activity is frequently much greater when the wearer breathes through the nose as compared with breathing through the mouth] and the respiratory flow pattern. Ideally any oscillatory activity which occurs should not be detectable subjectively; it must not be disturbing. Thus the double amplitude of any oscillation of pressure in the mask cavity which persists for longer than 0.25 seconds should not exceed 0.06 kPa.

4 Composition of Inspired Gas

4.1 Several physiological factors influence the requirements for the composition of the gas delivered to the respiratory tract. It is convenient to consider these requirements in terms of the limits to the concentration of oxygen in relation to cabin altitude. In conventional oxygen systems the diluting gas is virtually entirely nitrogen since the oxygen from the aircraft store is diluted with cabin air. The performance of molecular sieve oxygen concentrators is such that the product gas contains argon as well as oxygen and nitrogen. The maximum concentration of argon in the product gas is 5-6%. In this context argon has no specific physiological effects and can be regarded solely as an inert diluents gas.
The concentration of oxygen in the gas delivered by a breathing system to the nose and mouth not infrequently fluctuates during a single breath (especially in continuous flow oxygen systems) and from one breath to another (as occurs in some molecular sieve oxygen concentrator systems). The physiological requirements with respect to the concentration of oxygen in the inspired gas discussed in the following paragraphs assume that the inspired gas is thoroughly mixed before it enters the respiratory tract. In mechanical testing the mean volume weighed concentration of oxygen in the gas delivered to the mask cavity should be determined by passing the gas from the expiratory port of the mask through a mixing box fitted with baffle plates and measuring the concentration of oxygen in the mixed gas flowing from the box. The final definitive measure of the “effective” concentration of oxygen delivered by a breathing system is the measurement of the alveolar Po2 in human subjects breathing from the system during man rating. The composition of the alveolar gas may, with certain precautions, be determined in normal healthy subjects by measuring the Po2 and Pco2 of the gas flowing from the nose and mouth towards the end of expiration [the end-tidal Po2 and Pco2].

4.2 The composition of the gas which enters the respiratory tract during inspiration when wearing breathing equipment depends not only on the composition of the gas delivered to the oronasal mask (or pressure helmet) through the inlet hose, but also on the proportion of the tidal volume which is gas which had been breathed out in the previous expiration. The re-breathing of previously expired gas adds external dead space to the respiratory tract and lowers the concentration of oxygen delivered to the alveolar gas. It also impairs the elimination of carbon dioxide from the body which raises the alveolar Pco2 which in turn increases the pulmonary ventilation. The volume of the external dead space added by the oronasal mask (or pressure helmet) must therefore be minimised. Depending upon the shape of the cavity of the mask and the positioning of the inlet and outlet valves the effective respiratory dead space of a mask may be less than the volume of the mask cavity when the mask is sealed to the face of the wearer. The respiratory dead space added by most modern aircrew masks is of the order of 0.10-0.15 L(ATPD). The maximum acceptable effective respiratory dead space of an oronasal mask or pressure helmet is 0.2 L(ATPD).

Minimum Concentration of Oxygen in the Steady State

4.3 The principal consideration is that the concentration of oxygen in the inspired gas shall be adequate to prevent significant hypoxia. The partial pressure of oxygen Po2 in the alveolar gas when breathing air at ground level (barometric pressure - 760 mmHg) is normally 103 +3 mmHg. The ability of a subject to respond rapidly to a novel situation is marginally impaired when the alveolar Po2 is reduced to 75 mmHg by breathing air at an altitude of 5,000 feet and significantly reduced when the alveolar Po2 is reduced to below 60 mmHg by breathing air at altitudes greater than 8,000 feet. When breathing equipment is worn throughout flight as by the aircrew of high performance combat aircraft, the concentration of oxygen in the inspired gas is to be such that the alveolar Po2 is maintained at or above the value produced by breathing air at ground level, i.e. 103 mmHg. The alveolar Po2 should never be allowed to fall below 75 mmHg [the alveolar Po2 produced by breathing air at an altitude of 5,000 feet] during normal flight with the cabin pressurised. The devices employed in molecular sieve oxygen concentrator systems to provide warning when the Po2 of the product gas falls below an acceptable value have a significant tolerance band within which they may or may not provide a warning of a low Po2. In order to ensure that adequate warning of impending hypoxia is given without spurious warnings, the minimum Po2 of the product gas when the system is operating correctly should not be less than that required to maintain an alveolar Po2 of 103 mmHg. The warning system shall always provide a warning when the Po2 of the product gas falls below that required to maintain an alveolar Po2 of 75 mmHg.

4.4 The concentration of oxygen required at a given altitude to produce a given alveolar Po2 is calculated using the Alveolar Gas Equation with assumptions with respect to the partial pressure of carbon dioxide (Pco2) in the alveolar gas and the respiratory exchange ratio, R. The Alveolar Gas Equation states that

$$PAo2 = \frac{PIo2 - PAco2\,[\,FIo2 + (1-FIo2)\,]}{R}$$

Where

PAo2 = Po2 in alveolar gas
PIo2 = Po2 in inspired gas saturated with water vapour at 37°C
PAco2 = Pco2 in alveolar gas
FIo2 = Fractional concentration of oxygen in the mixed dry inspired gas
R = Respiratory Exchange Ratio

The normal resting value of the alveolar Pco2 is 40 mmHg and of R is 0.85. The concentration of oxygen required in the inspired gas and altitude to produce an alveolar Po2 of 103 mmHg is presented in Figure 1. The concentration of oxygen required in the inspired gas to maintain an alveolar Po2 of 103 mmHg rises to 100% at an altitude of 33,700 feet (barometer pressure = 190 mmHg). Above this altitude the alveolar Po2 will fall below 103 mmHg even when 100% oxygen is breathed.

4.5 Breathing systems for aircrew whether in aircraft in which an oxygen mask is worn throughout flight or in an aircraft in which the aircrew don oxygen masks only when the cabin altitude exceeds 8,000 feet should provide the minimum concentration of oxygen in the inspired gas in relation to cabin altitude which will maintain an alveolar Po2 of 103 mmHg [at cabin altitudes up to 33,700 feet]. Some degree of hypoxia is, however, acceptable in passengers in the emergency of loss of cabin pressure at altitude. Current UK Civil Aviation Authority and US Federal Aviation Agency specifications for passenger oxygen systems allow the mean concentration of oxygen in the inspired gas to fall to a level which will produce an alveolar Po2 of 55 mmHg at altitudes between 10,000 and 18,500 feet and an alveolar Po2 of 45 mmHg at altitudes above 18,500 feet.

Minimum Concentration of Oxygen to prevent Hypoxia on Rapid Decompression

4.6 A second factor which influences the relationship between the concentration of oxygen in the inspired gas and cabin altitude is the need to prevent impairment of performance due to hypoxia following a failure of the pressure cabin at high altitude. When the inspired gas breathed before the decompression contains a significant concentration of nitrogen, the fall of the total pressure of the alveolar gas produced by rapid decompression produces a concomitant reduction of the alveolar PO2 which may be to such a level that it produces impairment of performance or even unconsciousness. If the decompression is to an altitude greater than 30,000 feet then 100% oxygen must be delivered to the respiratory tract immediately the decompression occurs if there is not to be a significant impairment of consciousness. There will be a significant impairment of performance if the alveolar PO2 is reduced during the decompression to below 30 mmHg even for only a few seconds. If the magnitude of the area enclosed between an alveolar PO2 of 30 mmHg above and the time course of alveolar Po2 below exceeds 140 mm Hg.s then the individual will become unconscious. The decrement of performance at a choice reaction task is proportional to the magnitude of the area bordered above by a PO2 of 30 mmHg and the time course of the alveolar PO2 below. The breathing gas delivery system shall therefore prevent the alveolar PO2 falling below 30 mmHg during and subsequent to a rapid decompression.

4.7 The major factors determining the minimum value of the alveolar PO2 immediately after a rapid decompression are the initial and final absolute pressures of the alveolar gases, and the composition of the gases breathed before and after the decompression. Assuming that 100% oxygen is delivered to the respiratory tract immediately the decompression occurs, the alveolar PO2 can be prevented from falling below 30 mmHg by ensuring that the gas breathed before the decompression contains an adequate concentration of oxygen and that the total intrapulmonary pressure does not fall below 115-120 mmHg (15.3-16 kPa) absolute. Assuming that the duration of the decompression is so short that there is no significant exchange of oxygen between the alveolar gas and the blood flowing through the lungs, then the alveolar PO2 immediately after a decompression in which the absolute pressure of the lungs falls from PL (i) to PL (f) is related to the alveolar PO2 immediately before the decompression by the equation:

$$\text{Final alveolar PO2} = \text{Initial alveolar PO2} \times \frac{(PL(f)-47)}{(PL\,(i)-47)}$$

[all pressures expressed as mmHg]

4.8 This simple relationship may be employed to calculate the value of the alveolar PO2 before the decompression which will produce an alveolar PO2 of 30 mmHg immediately after the decompression from the initial to the final absolute pressures of the lung gas. The Alveolar Gas Equation (paragraph 4.4) can then be used to calculate the concentration of oxygen required in the inspired gas to ensure that the specified decompression will produce an alveolar PO2 of 30 mmHg (but no lower) immediately after decompression. The concentrations of oxygen required in the inspired gas to produce an alveolar PO2 of 30 mmHg immediately after a rapid decompression from a given initial cabin altitude to a given final cabin altitude [total absolute alveolar gas pressure at final cabin altitudes above 40,000 feet] are indicated by the interrupted curves of Figure 1. The relationship between initial cabin altitude and the final cabin altitude is determined by the pressurisation schedule of the cabin of the aircraft. The final alveolar gas pressure is also determined by the safety pressure/pressure breathing characteristics of the breathing gas delivery system. Thus the curve relating the minimum concentration of oxygen in the inspired gas to cabin altitude before a decompression required to prevent the alveolar PO2 falling below 30 mmHg immediately after the decompression will depend upon the cabin pressurisation schedule of the aircraft and the safety pressure/pressure breathing characteristics of the breathing gas delivery system.

4.9 The minimum inspired oxygen concentration-cabin altitude curves for two commonly used pressure breathing systems employed in aircraft with a cabin pressure differential of 35 kPa at aircraft altitudes above 23,000 feet are presented in Figure 1. Both of these pressure breathing systems commence pressure breathing at a cabin altitude of 40,000 feet and deliver oxygen at an absolute pressure which falls linearly with the reduction of environmental pressure at altitudes above 40,000 feet. One system employs a breathing pressure of 30 mmHg at 50,000 feet which provides an intrapulmonary pressure of 117.5 mmHg absolute at 50,000 feet. The other system employs a breathing pressure of 70 mmHg at 60,000 feet which provides an intrapulmonary pressure of 124 mmHg absolute at 60,000 feet. It may be seen from Figure 1 that the minimum concentration of oxygen required in the inspired gas to prevent significant hypoxia being induced by the rapid decompression is greater than that required to maintain an alveolar Po2 of 103 mmHg in the steady state at cabin altitudes above 16,000 feet. The concentration of oxygen required in the inspired gas at cabin altitudes above 16,000 feet is greater with the pressure breathing system which employs a breathing pressure of 30 mmHg at 50,000 feet than the system which employs a breathing pressure of 70 mmHg at 60,000 feet. The minimum concentration of oxygen required in relation to cabin altitude to prevent hypoxia in the steady state and in the event of a rapid decompression in an aircraft with a 35 kPa differential pressure cabin and using a breathing pressure of 30 mmHg at 50,000 feet is summarised in Figure 2.

Maximum Concentration of Oxygen

4.10 Breathing high concentrations of oxygen during flight in high performance, combat aircraft has two important disadvantages. It results in acceleration atelectasis and delayed otitic barotraumas.

4.11 Exposure to sustained positive acceleration whilst breathing high concentrations of oxygen produces marked collapse of the lower part of the lungs due to the absorption of alveolar gas whilst the small sized airways are collapsed by the increased weight of the lungs. The symptoms of the condition are attacks of coughing accompanied often by a sense of difficulty of breathing or, less frequently, by discomfort in the chest. The coughing is usually provoked by an attempt to take a deep breath either in flight or, more frequently, on standing up in the cockpit after flight. The cough and difficulty in breathing may last a few moments or repeated attacks may occur over a period of 10 to 15 min. Field studies have shown that 80-85% of pilots develop the condition with symptoms in flights in which 100% oxygen is breathed and manoeuvres above 3-4G are performed. The lung collapse which often reduces the vital capacity by 40% is associated with a large right to left shunt (20-25% of the cardiac output) of venous blood flowing through the collapsed lung, which reduces the concentration of oxygen in the arterial blood. The collapse remains after the return to +1 Gz until the individual takes a deep breath and/or coughs.

4.12 The causative factors of acceleration atelectasis are exposure to +Gz accelerations greater than 3-4G and breathing 100% oxygen. The degree of lung collapse and the intensity of the symptoms are greatly increased by inflation of the G trousers. The mechanism is absorption of gas from non-ventilated alveoli in the lower parts of the lungs. The ventilation of these alveoli ceases on exposure to +Gz acceleration as the increased weight of the lung above compresses the lower parts of the lung, closing the small and intermediate sized airways. Inflation of the abdominal bladder of the G trousers accentuates this process. A high concentration of nitrogen in the non-ventilated alveoli will maintain the patency of the latter whilst the increased accelerative force is operative and ventilation of the alveoli will recommence on return to 1G. If, however, the gas breathed before the exposure to +Gz acceleration is 100% oxygen so that the concentration of nitrogen in the alveoli is very low, the blood flowing through the non-ventilated alveoli rapidly absorbs all the gas trapped in the alveoli and surface forces maintain the alveoli in the collapsed state after the return to 1G until they are reopened by a deep inspiration and coughing. The rate of absorption of gas from non-ventilated alveoli is increased sixty times when 100% oxygen is breathed instead of air before the cessation of ventilation of the lungs. The presence of a significant concentration of nitrogen which has a much lower solubility in blood than oxygen and carbon dioxide acts as a brake on the absorption of gas from the non-ventilated alveoli.

4.13 Although no long term deleterious effects have been found in aircrew who have had the condition repeatedly in flight, many air forces consider that the chest discomfort which is produced and the potential hazard to safety of coughing in flight make acceleration atelectasis unacceptable. Acceleration atelectasis does not occur if the concentration of nitrogen in the gas breathed before and during the exposure to the sustained acceleration does not fall below 40%. In this context, the argon which is present in breathing gas produced by molecular sieve oxygen concentrators behaves as nitrogen as it is also relatively insoluble in blood. Laboratory studies suggest that the concentration of nitrogen required to prevent significant acceleration atelectasis at altitudes up to 25,000 feet is also 40%. Flight experience at cabin altitudes up to 20,000 feet confirms this finding.

4.14 Breathing 100% oxygen, especially if it is associated with ascent to and descent from even moderate altitudes, is followed in the vast majority of individuals by the development of ear discomfort and deafness (delayed otitic barotraumas). A typical picture is that, on waking from a night's sleep, following flights in which 100% oxygen has been breathed, the individual has discomfort in the ears and is moderately deaf. Examination of the ear shows that the eardrum is drawn into the middle ear and that there is fluid in the middle ear. Breathing 100% oxygen results in the nitrogen normally present in the middle ear cavity being washed out and replaced by oxygen through the pharyngo-tympanic tube. In the absence of nitrogen or the presence of a high concentration of oxygen in the middle ear cavity the blood flowing through the wall of the cavity rapidly absorbs gas from the cavity. The absorption of gas reduces the pressure in the middle ear which draws the eardrum into the cavity causing discomfort and deafness. The reduction in pressure also draws fluid into the cavity. The process of absorption of gas from the middle ear can be slowed and arrested after flight by "clearing the ears" whilst breathing air. The re-introduction of nitrogen into the middle ear must be repeated several times over the 12-18 hours following a flight in which 100% oxygen is breathed if delayed otitic barotraumas is to be avoided. However, if several ascents to altitude (even to only 5,000 feet) have been performed whilst breathing 100% oxygen the absence of ventilation of the middle ear which occurs during sleep results in ear discomfort and deafness the following morning.

4.15 The incidence of delayed otitic barotrauma is reduced by the presence of a minimum concentration of nitrogen in the gas breathed during flight. The concentration of nitrogen required in the inspired gas to reduce the incidence and severity of this condition to negligible levels is between 40% and 50%. Laboratory evidence suggests that the incidence of delayed otitic barotrauma will be very low when the nitrogen concentration is between 30% and 40%.

4.16 The requirements to avoid acceleration atelectasis and delayed otitic barotrauma in flight set the limit to the maximum concentration of oxygen which should be present in the gas delivered to the respiratory tract by the breathing system of a high performance combat aircraft. This requirement can be met by ensuring that the maximum oxygen concentration does not exceed 60%. There are obvious limits to the maximum altitude up to which this requirement can be applied. Three factors play a part in deciding the range of cabin altitudes over which it should be applied. The first factor is cabin pressurisation schedule. Aircrew operating combat aircraft will only be exposed to cabin altitudes greater than 20,000-22,000 feet in the rare event of decompression of the cabin at high altitude when 100% oxygen must be breathed in order to prevent hypoxia. The second factor is the effect of high altitude upon the ability of the aircraft to sustain significant levels of acceleration. The performance and operational roles of many current, high performances combat aircraft is such that the aircrew are very unlikely to be exposed to significant sustained +Gz accelerations at aircraft altitudes above 36,000 feet i.e. at cabin altitudes above 15,000 feet. Future agile combat aircraft will, however, be capable of exposing aircrew to significant levels of +Gz acceleration at aircraft altitudes greater than 35,000-40,000 feet. The third factor which is relevant is that the design of the breathing system becomes more technically difficult and costs rise if the difference between the minimum and maximum allowable oxygen concentrations is very small. Such would be the case if the specification of performance required that the concentration of oxygen should not exceed 60% at cabin altitudes much above 15,000 feet. Taking all these factors into consideration, the compromise requirement in current ASCC and NATO agreements is that the concentration of oxygen in the inspired gas delivered by the breathing system of an aircraft in which the aircrew will be exposed to sustained +Gz accelerations above 3G should not exceed 60% at cabin altitudes up to 15,000 feet and 75% at a cabin altitude of 20,000 feet (Figure 2).

5 Pressure Breathing at Altitude

5.1 The principal physiological hazards associated with loss of cabin pressure at altitudes above 40,000 feet are hypoxia, decompression sickness and cold injury. A full pressure suit assembly is necessary if protection against all three hazards is required over a prolonged period. However, if the aircraft can descent promptly and rapidly (within 3-4 minutes) to an altitude of less than 40,000 feet, protection against hypoxia only is required. A full pressure suit assembly will provide the ideal physiological protection, but it is bulky, cumbersome, impairs operational efficiency during routine flying with an intact cabin, and imposes major ground procedural problems. Pressure breathing combined with partial pressure garments at altitudes in excess of 50,000 feet is used therefore to provide short term or “get-me-down” protection against hypoxia. Partial pressure garments are required to combat the undesirable physiological disturbances produced by pressure breathing, but in order to exploit the advantages of the partial pressure approach (less restriction when un-inflated and inflated, greater routine comfort and lower thermal load), it is desirable that the area of the surface of the body to which counter pressure is applied should be the minimum required to provide the specified protection. Thus the design of the counter pressure garments represents a compromise between ideal physiological requirements and functional convenience. In addition, since the protection against hypoxia using a partial pressure assembly is required for only a short period of time during emergency descent, some compromise in the level of alveolar Po2 which is required is also acceptable. It is the interaction of the deleterious effects of hypoxia upon mental performance and the cardiovascular system, with the undesirable consequences of positive pressure breathing, which determine the acceptable minimum alveolar PO2. Virtually all pressure breathing systems and partial pressure assemblies employ 100% oxygen in order to minimise the magnitude of the breathing pressure required at altitudes above 40,000 feet to maintain the required alveolar PO2. The use of product gas from a molecular sieve oxygen concentrator comprising 5-6% argon and 94-95% oxygen during pressure breathing at an altitude of 50,000 feet, requires the breathing pressure to be increased in order to maintain the alveolar PO2 at the appropriate level.
Pressure breathing with a pressure sealing mask and no counter pressure to the body is widely used to provide short duration protection against hypoxia on exposure to altitudes up to 48,000-50,000 feet. The mean mask cavity pressure required at 50,000 feet is a compromise between too high a pressure which will produce a faint, and too low a pressure which will not prevent a serious deterioration of performance due to hypoxia. The acceptable compromise is a mean mask pressure between 4.0 and 4.5kPag (30.0-33.8 mmHg) at 50,000 feet.
Between 38,000 feet and 50,000 feet the mean mask pressure should increase linearly with fall of environmental pressure, the limits of mean mask pressure at 40,000 feet being +0.1 to 1.0 kPag (0.75-7.5 mmHg). During pressure breathing with a mask alone the total change of mask cavity pressure during the respiratory cycle should not exceed 0.5 kPa at peak inspiratory and expiratory flows of 0.5 L(ATPD) s-1 and 1.0 kPa at peak inspiratory and expiratory flows of 1.83 L(ATPD) s-1 [the absolute pressure in this context is the absolute pressure in the mask and respiratory tract].

5.2 The magnitude of the breathing pressure required to prevent unacceptable hypoxia at altitudes above 50,000 feet requires the application of counter pressure to the chest and abdomen to support breathing and at higher altitudes counter pressure to at least a portion of the limbs to counteract the effects of the raised intrapulmonary pressure upon the cardiovascular system, and maintain an adequate arterial blood pressure and blood flow to the brain. Thus all partial pressure assemblies apply counter pressure to the external surface of the chest, most commonly by means of a bladder covering part or the entire chest and restrained within an outer inextensible fabric layer. The bladder is connected into the hose between the breathing gas demand regulator and the oronasal mask/pressure helmet so that it is inflated with breathing gas to the breathing pressure provided by the regulator. The bladder of the pressure jerkin not only applies counter pressure to the chest, but also to the whole of the abdomen which ensures the minimum of respiratory disturbances during pressure breathing. In some partial pressure assemblies counter pressure is applied to the abdomen and lower limbs by means of the G trousers which the crew member is primarily wearing to enhance tolerance of +Gz acceleration. The pressure in the G trousers during pressure breathing at altitude is raised to 1.5 to 3.2 times the breathing pressure. The optimum ratio of G trouser to breathing pressures varies with the degree of coverage provided by the G trousers and is about 2.0 when using the UK full coverage anti-G trousers.

5.3 The excellent sealing properties of the RAF type P/Q oronasal masks developed in the late-1950s introduced the possibility of replacing cumbersome partial pressure helmets by an oronasal mask in short duration partial pressure assemblies. A well-sealing oronasal mask can be used to deliver breathing pressures of up to 9.3 kPag (70 mmHg) for several minutes. A limited proportion of subjects can even tolerate pressure breathing with a mask at pressures up to 10.7 kPag (80 mmHg). The practical limit to the use of an oronasal mask without external support to the upper neck is a breathing pressure of 9.3 - 10.0 kPag (70-75 mmHg). The standard of sealing of a mask employed to deliver high pressures to the respiratory tract should be such that the outboard leakage from the mask when sealed to the face does not exceed 0.10 L(ATPD) s-1 at a mask pressure of 4 kPa and 0.25 L(ATPD) s-1 at a mask pressure of 9.3 kPa. If any leakage does occur during pressure breathing the fit of the mask should be adjusted so that the leaks do not occur into the eyes.

5.4 Partial pressure assemblies which employ a partial pressure helmet to deliver 100% oxygen to the respiratory tract maintain the absolute pressure in the lungs at 18.7-20.0 kPa (141-150 mmHg) at all altitudes above 40,000 feet which, in the absence of hyperventilation, gives an alveolar PO2 of 50-60 mmHg. The use of a breathing pressure of only 30 mmHg at 50,000 feet results in an intrapulmonary pressure of 117 mmHg (15.6 kPa) absolute and an alveolar PO2 of 40 mmHg with a moderate degree of hyperventilation (alveolar PCO2 = 30 mmHg). When pressure breathing is performed with an oronasal mask and counter pressure to the trunk and lower limbs at breathing pressures up to 70 mmHg (9.3 kPag) an intrapulmonary pressure of 130 mmHg (17.3 kPa) absolute produces mild to moderate impairment. Several current partial pressure assemblies comprising an oronasal mask with counter pressure to the trunk and lower limbs employ a breathing pressure of 70 mmHg (9.3 kPag) at an altitude of 60,000 feet, which provides an intrapulmonary pressure of 124 mmHg (16.5 kPa) absolute and an alveolar PO2 of 45-50 mmHg. The relationship of breathing pressure (mask pressure) to altitude between 40,000 and 60,000 feet can take several forms (Figure 3). The mask pressure can be held at 141 mmHg (18.8 kPa) absolute with ascent above 40,000 feet until the breathing pressure reaches the maximum of 70 mmHg (9.3 kPag) [Figure 3 - solid line]. This relationship minimises the hypoxia at the intermediate altitudes. An alternative relationship is one in which the absolute pressure in the mask falls linearly with environmental pressure from 40,000 to 60,000 feet [Figure 3 - broken line]. This form of the relationship minimises the cardiovascular stress at the intermediate altitudes. The mask pressure meaned over the respiratory cycle during pressure breathing at altitudes over 40,000 feet is to be within 0.27 kPa of the nominal mask pressure. Partial pressure breathing systems employing an oronasal mask, trunk counter pressure (pressure waistcoat and G trousers or pressure jerkin) and G trousers have been shown to be effective and acceptable to aircrew at altitudes up to 60,000 feet. There is at present an insufficient body of evidence to support their use to provide protection at altitudes above 60,000 feet.

5.5 The resistance to breathing during pressure breathing with respiratory counter pressure is determined by the relationships of the pressures in the mask cavity, the pressure applied to the chest by the respiratory counter pressure garment [which is generally assumed to be the pressure in the bladder, if a bladder system is used] and the pressure applied to the abdomen by the G trousers. The swings of pressure in the mask cavity and the chest counter pressure garment during pressure breathing with counter pressure should not exceed the limits specified in Table 2. The difference between the pressure in the mask cavity and the chest counter pressure garment shall at no time exceed 0.5 kPa.

5.6 The required intrapulmonary pressure must be established rapidly on a sudden decompression to high altitude if hypoxia is to be avoided. Thus on a rapid decompression (in 0.1 s) to an altitude above 45,000 feet the pressures in the mask cavity and in the respiratory counter pressure garment shall not fall below 120 mmHg (16 kPa absolute) for longer than 2 s. This standard determines the requirement for the rate of inflation of the respiratory counter pressure garment. In practice, however, where the garment will usually be inflated to safety pressure prior to a decompression, there is a need to vent excess gas from the garment to avoid over-pressurisation, although the latter can provide some protection against lung damage on a very rapid decompression.

6 Pressure Breathing for +Gz Protection

6.1 Pressure breathing with chest counter pressure and G trouser inflation is now a well-established technique for raising the tolerance of +Gz accelerations. Pressure breathing with chest counter pressure together with extended cover G trousers will maintain full consciousness and vision in seated relaxed subjects during prolonged exposures to +8 to +9Gz. As with pressure breathing at altitude assemblies, the bladder of the chest counter pressure garment is connected into the breathing gas hose between the pressure demand regulator and the oronasal mask. The pressure demand regulator provides pressure breathing in response to the rise in the pressure at the outlet of the anti-G valve. The latter typically controls the flow of cooled engine bleed air into and out of the G trousers. The anti-G valve inflates the G trousers rapidly (within 1-2 s) to the desired pressure in relation to the total applied +Gz. The relationship between pressure in the G trousers and applied G is trouser pressure rising linearly with acceleration from 0 at 2G to 72 kPag at 9G.

6.2 The optimum breathing pressure at 9G is 60-65 mmHg (8.0-8.7 kPag). The preferred relationship is to commence pressure breathing at 4G and for the breathing pressure to rise linearly to 60-65 mmHg (8.0-8.7kPag) at 9G. There may be an advantage in delaying the onset of pressure breathing to a higher level of acceleration in order to minimise the incidence and severity of arm pain in cockpits where the hands are positioned below heart level.

6.3 The resistance to breathing during pressure breathing with G should be minimal. The total swing of mask pressure should not exceed the limits specified in Table 2. The difference between the pressures in the chest counter pressure garment and the mask cavity should not exceed 0.5 kPa. Pressure breathing must not be operative unless the G trousers are pressurised as pressure breathing on exposure to +Gz acceleration without pressurisation of the G trousers will cause rapid loss of consciousness. The inflation of the chest counter pressure garment and the rise of pressure in the mask and garment on the sudden application of +Gz must not lag more than 0.5s behind the rise of pressure in the G trousers. The chest counter pressure garment should also deflate rapidly on cessation of exposure to +Gz acceleration.
The fall of pressure in the mask and chest garment should not lag more than 0.5s behind the fall of pressure in the G trousers.

7 Pressure Breathing - Press-to-Test

7.1 A facility whereby pressure breathing may be obtained by the operation of a manual control is required to enable the user to test the standard of seal of the breathing gas delivery system up to and including the mask. The performance of this facility is to be such that the user can perform several respiratory cycles with the mask pressure raised.

7.2 The test pressure to be employed varies with the pressure breathing assembly in use. The mean mask pressure produced on press-to-test when a mask is worn alone should be within the limits +3.5 to +4.5 kPag. When chest counter pressure and G trousers are worn for protection on decompression at high altitude the facility should provide a mask pressure of 6.7 to 8 kPag and inflation of the G trousers to 1-2 times breathing pressure. This mask pressure is also to be provided in a press-to-test facility for a pressure breathing with G assembly. It should be noted that it is not acceptable to provide this facility simply by inflating the G trousers to the appropriate pressure, 62-72 kPag, as the application of these G trouser pressures at +1Gz gives rise to severe pain. The total change of mask cavity pressure during the operation of the press-to-test facility should not exceed 0.75 kPa at peak respiratory flows of 0.5L (ATPD) s-1 and 1.0 kPa at peak flows of 1.0L (ATPD) s-1.

8 Protection against Hypoxia after Ejection

8.1 The delivery of breathing gas to the respiratory tract following ejection from an aircraft at altitude shall be such that significant hypoxia does not occur during the subsequent descent of the crew member to below 10,000 feet.

Typical descent times from various altitudes to 10,000 feet are presented in Table 4.

Starting Altitude (feet)	Time to descent to 10,000 feet (second) Man Alone	Man in ejection seat*
20,000	40-60	70
30,000	70-110	130
40,000	95-160	170
50,000	110-190	215
60,000	130-220	245

Table 4 - Time to descend to 10,000 feet following ejection
* Ejection seat with 1.62 m diameter drogue

8.2 The time taken to descend from altitudes up to 20,000-25,000 feet is such that breathing air throughout the whole of the descent will not cause significant impairment of performance. Thus it is not essential to provide supplemental oxygen for escape at altitudes up to 25,000 feet. Breathing gas with a PO2 greater than 130-150 mmHg is required to prevent hypoxia on escape at altitudes above 25,000 feet. Pressure breathing is required at altitudes above 40,000 feet. Inward relief whereby the ejectee/parachutist can breathe ambient air in the event of either cessation of the breathing gas supply or separation from the ejection seat, is required. The headgear including the mask and its supply system must remain intact and remain in place during ejection and perform satisfactorily thereafter. The breathing equipment must perform satisfactorily at low temperature (-60°C) in the presence of representative air movement [at least 20 knots (37km.h-1)].

9 Provision of Inward Relief

9.1 The ability to breathe air is required in the event that the flow of breathing gas provided by the breathing equipment is inadequate to meet the inspiratory demand. This facility is necessary in order to avoid a sudden failure of the supply of breathing gas imposing a very high resistance to inspiration, a situation which could threaten flight safety.
The inward relief facility must not allow the ambient air to dilute the breathing gas delivered by the breathing system during normal operation of the equipment and thereby cause hypoxia or allow toxic material in the cabin air to enter the breathing system. The crew member should be aware immediately that air is entering the breathing system. In many conventional breathing systems inward relief is obtained either by loosening the mask so that air can be inspired around it or by disconnecting the inlet hose of the mask from the supply system. Neither of these methods is satisfactory. Some systems employ a spring-loaded inward relief valve (anti-suffocation valve) in the wall of the mask or mask hose connector. The minimum suction required to open such an inward relief valve should be 1.25 - 1.75 kPag in order to ensure that the opening of the valve is noticed immediately by the wearer but that the inspiratory resistance is acceptable for breathing up to at least 30 minutes and it will not depress the respiration of an unconscious crewmember.

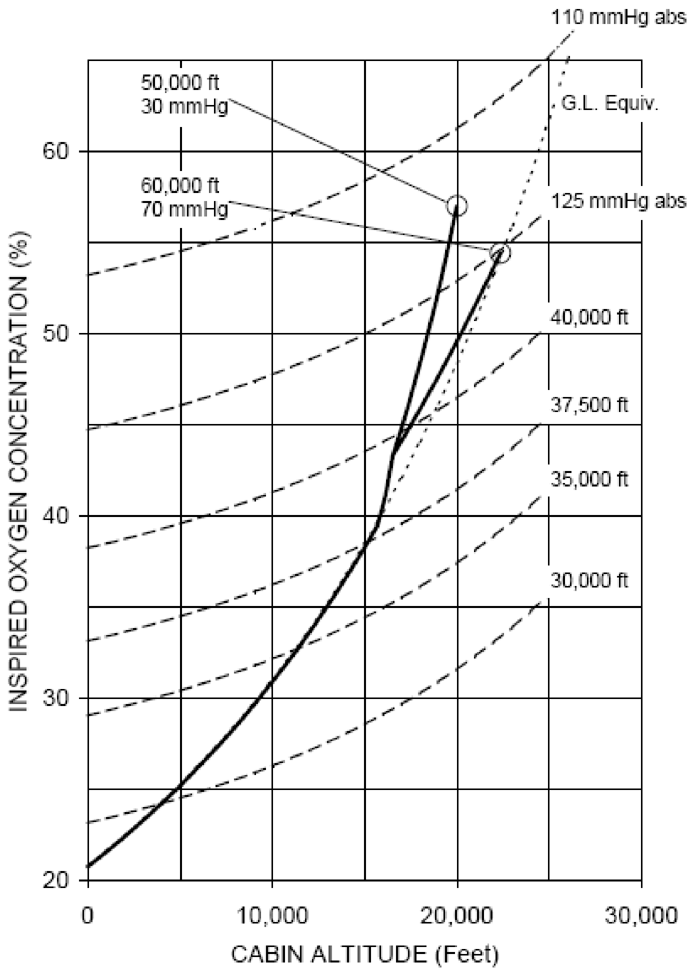

Figure 1

The relationships between the concentration of oxygen in the inspired gas and cabin altitude required (i) to maintain an alveolar Po2 of 103 mmHg - GL equivalent; (ii) to produce an alveolar Po2 of 30 mmHg on rapid decompression to various final altitudes and intrapulmonary pressures - broken lines and (iii) to ensure rapid decompression of a 35 kPag pressure cabin will produce a minimum alveolar Po2 of 30 mmHg when using two common pressure breathing schedules at altitudes above 40,000 feet - solid lines.

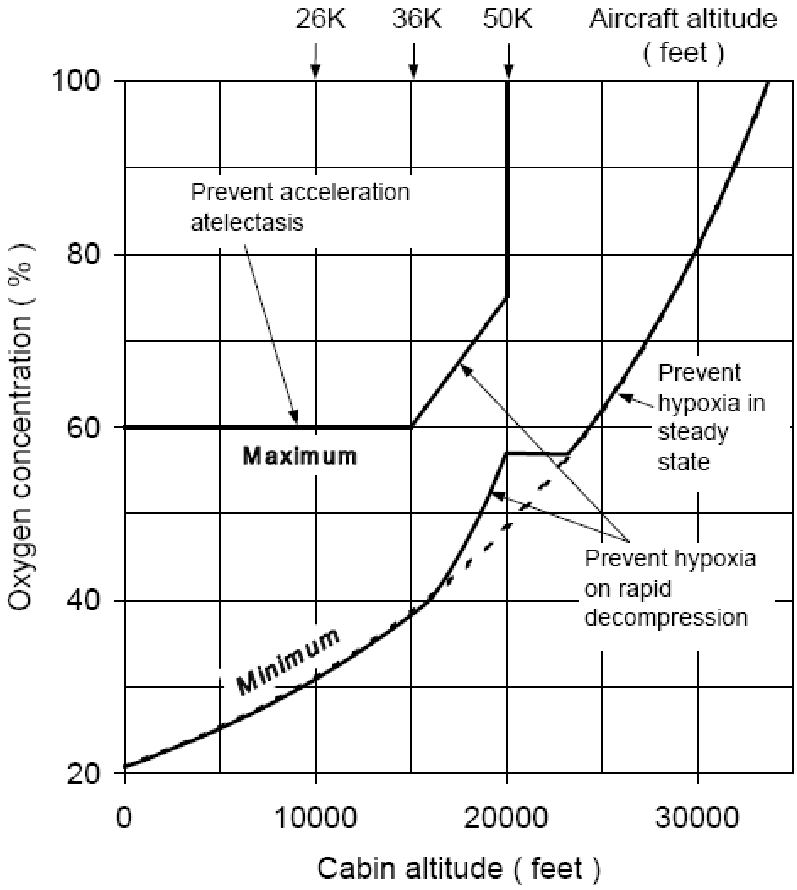

Figure 2

A specification embodying the physiological requirements for the relationship of the concentration of oxygen in the inspired gas and cabin altitude in the intact pressure cabin of a typical agile combat aircraft with a 35 kPag pressure cabin and a ceiling of 50,000 feet.

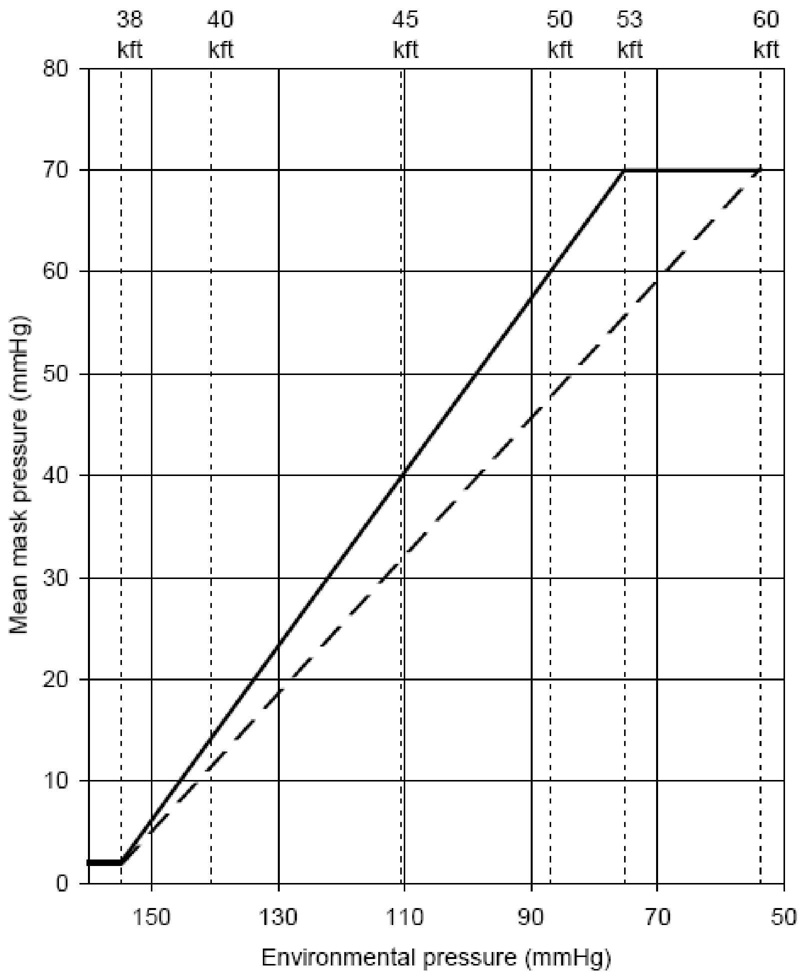

Figure 3

Two acceptable forms of the relationship between mean mask pressure and altitude for a partial pressure assembly comprising a mask, pressure waistcoat or jerkin and G trousers.
Note that both of these lines are nominal relationships - in practice, engineering tolerances would require that upper and lower limits be defined around either line (or any other acceptable line) based on aeromedical and engineering discussion.

Proposed Text Part 13

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SECTION 2

LEAFLET 3

OXYGEN SYSTEMS

PHYSIOLOGICAL REQUIREMENTS FOR OXYGEN SYSTEMS

1 Introduction

1.1 This leaflet describes the basis of the physiological requirements for breathing systems which are fitted to aircraft primarily to provide individual protection against hypoxia for aircrew and passengers. Breathing equipment is also employed to provide protection against the inhalation of toxic gases and fumes which may arise in the cabin environment and of airborne nuclear, biological and chemical (NBC) warfare agents. Recently the delivery of positive pressure breathing has been adopted as a means of enhancing aircrew tolerance of high sustained +Gz accelerations (pressure breathing with G, PBG). Breathing equipment may, by the composition of the gases delivered to the respiratory tract and/or the associated impedance to breathing induce undesirable or indeed unacceptable physiological and/or performance disturbances in the individual.

1.2 The physiological requirements for the performance of aircraft breathing systems represent practical compromises between the physiological ideal that the equipment should produce no disturbance whatsoever to the user, the performance of available designs and the operational and logistic requirements of simplicity, reliability, low maintenance and low financial cost. They are based upon laboratory and airborne research and operational experience. As the requirements are compromises they may vary with the application. Thus the degree of hypoxia which is acceptable in seated passengers following decompression of the cabin of an aircraft at high altitude differs markedly from that which is acceptable in the pilot of high performance combat aircraft during flight with the cabin pressurised.

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1.3 The design and operation of an aircraft breathing system must be very closely related to the breathing requirements of the wearer. The three major aspects of these are the respiratory flow demands, the pressure at the entrance to the respiratory tract (nose and mouth) and the composition of the gas which is delivered to the respiratory tract. The physiologically acceptable values of these breathing requirements are addressed in this leaflet together with the other physiological factors which affect the performance of aircraft breathing systems.

2 Respiration in Flight

2.1 The ranges of instantaneous and average flow rates which can be demanded by fit adults are extremely large. Thus the peak inspiratory flow rate can vary from 0.4 - 0.5 L (BTPS) s^{-1} at rest to 10 L (BTPS) s^{-1} in maximum exercise, and the mean inspired pulmonary ventilation from 6 L (BTPS) min^{-1} at rest to 150 L (BTPS) min^{-1} in maximal exercise. Whilst it is self-evident that aircrew will not perform maximal exercise in flight a pilot who climbs into the cockpit of his aircraft after running may well have a very high respiratory demand. Knowledge of the pulmonary ventilation (average inspiratory or expiratory flow) and the instantaneous respiratory flow rates demanded by aircrew (and passengers) in flight and on the ground is essential for the specification of the performance required of an aircraft breathing system. Thus the pulmonary ventilation which occurs under various conditions of flight will determine the size of the main, back-up and emergency

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stores of oxygen required in an aircraft. Knowledge of the ranges of pulmonary ventilation which may be demanded by aircrew over relatively short periods of flight [30 seconds or so] is required for the specification of the performance of molecular sieve oxygen concentrator systems. Finally the impedance to respiration imposed by any breathing system is a function of the instantaneous inspiratory and expiratory flow rates created by the wearer.

Effect of Altitude

2.2 The gases in the lungs are always saturated with water vapour at body temperature (37°C) so that the partial pressure of water (PH_2O) in the alveolar gas is always 47 mmHg. These conditions of a temperature of 37°C and a PH_2O of 47 mmHg are termed body temperature, pressure and saturated with water vapour (BTPS). Thus as a dry gas at ambient pressure and temperature (ATPD) enters the lungs, it expands, not only due to the rise in temperature, but also due to the addition of water vapour. Whilst the increase in volume due to a change of temperature from the standard temperature of NTPD conditions (15°C) to 37°C of 7.6% is independent of changes in ambient pressure, the increase in the volume of the gas due to the PH_2O rising from 0 to 47 mmHg varies with altitude from 6.6% at ground level, to 14.1% at 18,000 feet and 50% at 40,000 feet. Whilst the dependence of the relationship between gas volumes at ATPD and BTPS conditions upon ambient pressure (altitude) is of great importance in calculating the size of oxygen stores this effect is normally neglected when considering instantaneous respiratory flow rates over the normal range of cabin altitudes. Indeed specifications of instantaneous flow rates are by convention considered to be unaffected by altitude and are stated as flow rates of dry gas at 15°C and at the absolute pressure within the respiratory tract (mask cavity) (ATPD). These conventions are followed in the ASIC Standards and NATO STANAGS and in Section 1 Clause 1.4

2.3 The level of pulmonary ventilation of an individual in the absence of hypoxia and emotional disturbances is very closely related to the rate of production of carbon dioxide by the body, which in turn is very closely related to the physical activity of the individual. Generally, pulmonary ventilation is adjusted in relation to the rate of production of carbon dioxide to maintain a constant partial pressure of carbon dioxide (PCO_2) in the alveolar gas and the arterial blood. Thus at a constant level of activity (rate of production of carbon dioxide) the pulmonary ventilation expressed as volume under BTPS conditions is unaffected by ascent to altitude, provided that the concentration of oxygen in the inspired gas is raised in order to prevent any hypoxia (see below).

Average Pulmonary Ventilation

2.4 The maximum average pulmonary ventilation is the essential component of any calculation of the quantity of gas required to supply aircrew using a demand type of flow regulated breathing system. The value used for the latter must take into account the effects of various stages of a sortie and of types of flight on pulmonary ventilation, and the variation in the individual responses to each condition. Extensive flight trials in combat aircraft the UK in the early 1960s led to the adoption of the maximum [to include 97% of occurrences] pulmonary ventilations, averaged over the whole sortie of the crews of combat aircraft presented in Table 1. Equivalent data for the front and rear crews of large aircraft are not yet available. Increasing the number of crew will reduce the mean pulmonary ventilation per individual as it is very unlikely that the pulmonary ventilations of several crew members will be at the maximum value measured for a single crew member. Flight trials conducted in fighter and bomber aircraft in the early 1960s formed the basis of the values presented for multiple crews in Table 1. These values together with the air dilution characteristics of the MK17, 20 and 21 series of pressure demand regulators form the basis of the oxygen requirements for aircrew in Section 1.4. Measurements of pulmonary ventilation in mock air-to-air combat in a Hunter T7 aircraft yielded a mean value for 18 pilots of 18.8 L (BTPS)min-1 with a maximum average value (to include 97% of all observations) of 24L(BTPS)min^{-1}. Measurements of pulmonary ventilation in 12 rotary wing rear crew in a ground based simulation of flight tasks yielded a mean value of 13.9 L (BTPS) min^{-1} at rest, and pulmonary ventilation measured in 12

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Pulmonary Ventilation of Aircrew operating combat aircraft averaged over a sortie [values to include 97% of occurrences].	
Number of Seats in aircraft	**Average Pulmonary Ventilation (L (BTPS) min^{-1})**
1	21.8
2 or 3	18.6
4 or more	16.2

Table 1. Pulmonary ventilation of aircrew operating combat aircraft.

2.5 It should be emphasised that the values for maximum average pulmonary ventilation over complete sorties presented in Table 1 should be used with caution in circumstances outside those in which the information on which they are based was collected. Although estimates of the quantity of oxygen required in aircraft storage systems in UK military aircraft have been based upon these values for pulmonary ventilation since the early 1960s the adoption of standard sizes of LOX converters in the mid-1960s led in general to the capacity of the oxygen store being greater than that required by the values presented in Table 1. This greater margin of oxygen supply would tend to mask in service any underestimate of the quantity of oxygen required based on the values in Table 1.

Minimum and Maximum Pulmonary Ventilation

2.6 The pulmonary ventilation of an aircrew member may vary markedly with time during a flight. Thus pulmonary ventilation is typically raised during the stress of take-off and landing. It is raised by flight at low level and when performing the anti-G straining manoeuvre and by air combat. The minimum and maximum levels of pulmonary ventilation which may occur in flight are of importance to certain aspects of the design of breathing systems, such as the performance of the injector form of air dilution mechanism employed in many demand regulators and the concentration of oxygen in the product gas provided by a molecular sieve oxygen concentrator. In this context the relevant value of the pulmonary ventilation is typically that averaged over a period of 30 seconds or longer. The minimum pulmonary ventilation which will be demanded by a pilot during undisturbed straight and level flight or by a seated passenger is very similar to the minimum seen in subjects seated at rest on the ground i.e. 6.0 L (BTPS)min^{-1}. Thus the value for the minimum pulmonary ventilation to be met by aircraft breathing systems used by either aircrew or passengers adopted in current national and international standards is **5.0 L (ATPD) min^{-1}**.

2.7 The few studies which have been made of maximum pulmonary ventilation in flight in pilots performing simulated aerial combat and other manoeuvres have yielded values between 51 and 60 L(BTPS) min^{-1} for the maximum pulmonary ventilation maintained for 30 seconds or longer. Values higher than 40 L (BTPS) min^{-1} were recorded on 1-2% of occasions. Although there are no data for large aircraft crews available, pulmonary ventilation measured in 12 rotary wing rear crew in a ground based simulation of flight tasks yielded a mean maximum value of 66.7 L (BTPS) min^{-1} during brief heavy exercise before landing. In 12 rotary wing pilots, pulmonary ventilation measured in a flight simulator showed a mean value of 19.1 L (BTPS) min^{-1} during complex flight. The standard adopted by the ASIC and NATO nations for the maximum pulmonary ventilation which can be sustained in flight for 30s or more is **50 L (ATPD) min^{-1}**. It is unlikely that the flight deck crew of transport aircraft would exhibit pulmonary ventilations as high as 50 L(ATPD) min^{-1}, whilst seated in flight. A realistic value for the maximum pulmonary ventilation to be sustained by these aircrew for 30 seconds or longer is 40 L (ATPD)min^{-1}. The maximum pulmonary ventilation demanded by flight deck crew when moving out of their seats may well, however, exceed 50 L (ATPD) min^{-1}. A sustained pulmonary ventilation of 50 L (ATPD) min^{-1} would be demanded by an aircrew member fighting an in flight fire. The pulmonary ventilations of seated passengers will

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1 21.8¶
2 or 3 18.6¶
4 or more 16.2¶
Table 1 - Pulmonary Ventilation of Aircrew operating combat aircraft¶
2.5 An alternative approach is that presented in US Military Standard MIL-D-19326H, Oct 78 which employs baseline pulmonary ventilations for the calculation of the ventilation averaged over the whole sortie of 18.0 L (BTPS) min-1 for a single pilot and 16.5 L (BTPS) min-1 for each of a two man crew. The MIL standard increases the baseline pulmonary ventilation by 75% when the aircraft is engaged in aerial combat and by 25% when terrain following. Calculations of maximum average pulmonary ventilations for comparable fighter and bomber sorties using the MIL-D- 19326H approach yield values in reasonable agreement with the values for pulmonary ventilation presented in Table 1.¶

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under normal flight conditions vary between 5 and 20 L (ATPD) min^{-1}, depending upon their level of activity. The emotional disturbances, such as fear, which may be engendered by decompression of the cabin can raise the pulmonary ventilation of passengers above this range. European Aviation Safety Authority and US Federal Aviation Agency requirements for passenger breathing equipment specify a maximum sustained pulmonary ventilation of **30 L (BTPS) min^{-1}**.

Instantaneous Respiratory Flow Rates

2.8 The instantaneous rates of flow of gas into and out of the respiratory system is one of the principal factors which determine the magnitude of the changes in mask pressure imposed by a breathing gas delivery system, the other being the pressure-flow characteristics of the breathing equipment itself. There is considerable variation in respiratory flow patterns between individuals, especially when breathing at rest. Typically, the breathing frequency is 15 breaths a minute with each inspiration occupying 1.6 seconds and each expiration lasting 2.4 s. During inspiration the instantaneous flow typically rises rapidly to a maximum after 0.5 seconds and then falls at a slower rate to zero. Expiration usually follows the end of inspiration without a break. The instantaneous flow in expiration rises to reach a maximum which is somewhat less than the maximum attained in inspiration. The flow then declines slowly to reach zero at the end of this phase of the cycle. There is frequently a pause between the end of expiration and the commencement of the next inspiration. Of particular significance to the design of aircraft breathing systems are the maximum (peak) inspiratory and expiratory flows which occur during the respiratory cycle. Although for some purposes the instantaneous respiratory flow can be simulated by a sine wave (when the peak flow equals 3.14 times the pulmonary ventilation) the peak inspiratory flow at rest is typically 3.2-3.8 times the pulmonary ventilation, and the peak expiratory flow is about 2.7 - 3.0 times the pulmonary ventilation. Respiratory flow patterns tend to become more regular as the pulmonary ventilation is increased by physical exercise. Inspiratory and expiratory times become more equal as do peak inspiratory and expiratory flow. Moderate increases of pulmonary ventilation produced by physical exercise typically occur by an increase in the size of individual breaths (i.e. increase of tidal volume) rather than an increase in the frequency of breathing. When the respiratory frequency increases it principally occurs by a shortening of the duration of expiration; the duration of inspiration only decreases slightly with increasing frequency of breathing.

2.9 Respiratory flow patterns are modified by numerous factors ranging from exercise, speech and swallowing to the imposition of external resistance to breathing (see paragraph 3.1) and pressure breathing. Of particular relevance to the requirements for aircraft breathing systems are the changes produced by speech and the anti-G straining manoeuvre (AGSM). The duration of inspiration is markedly reduced by speech and since there are usually only minor changes in the tidal volume the peak inspiratory flow is increased to 5 to 10 times the pulmonary ventilation. The expiratory flow is modulated during speech and the maximum flow is less than that during breathing at the same level without speech. The voluntary breathing manoeuvres involved in the AGSM greatly reduce the duration of inspiration and expiration. The breathing cycle is typically completed in 1.0-1.5 seconds and the peak inspiratory and expiratory flows are increased to between 7 and 15 times the pulmonary ventilation. Pressure breathing without counter-pressure to the chest also produces marked changes in respiratory flow patterns with an increase in peak inspiratory flow and expiration becoming prolonged with a relatively constant expiratory flow. The application of full counter-pressure to the chest tends to restore the breathing flow patterns to those seen in the absence of pressure breathing. The flow patterns during pressure breathing with +Gz acceleration with counter-pressure applied to the chest and abdomen are similar to those which occur in light to moderate exercise provided that the individual does not perform any respiratory straining manoeuvre.

2.10 The specifications of the maximum peak flows to be met by aircraft breathing systems are based principally upon the breathing patterns of aircrew recorded in flight. These have shown that the peak inspiratory and expiratory flow of pilots operating high performance combat aircraft can be

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as high as 5L (ATPD) s^{-1}. Analysis of the frequency distributions of peak flow recorded in several in flight studies has shown that the occurrence of peak flows in excess of 3.3L (ATPD) s^{-1} is 2.5%. ASIC and NATO specifications require that breathing systems must be capable to meeting peak inspiratory and expiratory flows of at least 3.3 L (ATPD) s^{-1}. Ideally aircraft breathing systems should be capable of meeting peak flows of up to 4.2L (ATPD) s^{-1}. Since speech at moderate levels of pulmonary ventilation (20L (ATPD) min^{-1}) will produce peak inspiratory flows of 2.5-3.3 L (ATPD) s^{-1} breathing systems designed for use in multi-crew aircraft, including transport aircraft, must also be capable of meeting peak inspiratory flow rates of 3.3L (ATPD) s^{-1}.

2.11 In pressure demand breathing systems, the impedance to respiration imposed by the system is a function not only of the instantaneous respiratory flow, but also the rate of change of flow. The rates of change of flow which occur during breathing are related to the nature of the respiratory manoeuvre e.g. quiet breathing, speech, AGSM, pressure breathing and also to a limited extent the peak respiratory flow. Speech at rest increases the median rate of onset and offset of inspiratory flow during quiet breathing from 1.6 L s^{-2} to 18 L s^{-2}. In practice, the highest rates of change of flow occur in speech and whilst performing the AGSM. The minimum rates of change of inspiratory and expiratory flow specified by ASIC and NATO requirements for aircrew breathing systems are 10L (ATPD) s^{-2} at a peak flow of 1.5 L (ATPD) s^{-1} increasing to 20 L (ATPD) s^{-2} at a peak flow of 3.3 L (ATPD) s^{-1}. These rates of change of flow define the rate of change between 0 flow and 90% of the relevant peak flow.

2.12 As already discussed (paragraph 2.4) it is unlikely that the breathing patterns of the members of two crew or multi-crew aircraft will coincide exactly in time. Monte Carlo simulation of the inspiratory demands of two crew members suggests that 95% of all instantaneous peak demand flow can be met by a breathing system which will provide 70% of the flow demanded when the two crew members are breathing exactly in phase. An in-flight study in which the inspiratory flow patterns of the two crew of a two seat combat were recorded during level flight, high G aerobatics and simulated combat manoeuvring, showed that the beginning of inspiration occurred simultaneously in the two pilots in less than 1% of 5,000 breaths. The UK standard requires that a breathing system for two crew members provides 85% of the peak inspiratory flow which could be demanded by both crew members breathing exactly in phase i.e. 5.6L (ATPD) s^{-1}.

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3 Resistance to Respiration

Effects of external resistance

3.1 Excessive external resistance to breathing can give rise to breathing discomfort, fatigue of the respiratory muscles and to changes in pulmonary ventilation which generally causes hypoventilation but on occasions can cause hyperventilation. Excessive resistance also impairs speech and the ability to perform the ASGM. Finally, changes in the mean pressure in the lungs induced by external resistances can disturb the cardiovascular system and the distribution of body fluids. Many laboratory based studies of the effects of adding external impedances to breathing have employed resistances which had a linear relationship between pressure drop and flow rate. Such studies showed that subjective discomfort occurred when resistances with a pressure drop greater than 0.5 kPa at a flow of 1.4 L (ATPD) s^{-1} were imposed in inspiration and expiration together. Other studies in which the additional work of breathing produced by a variety of levels of external resistance was measured suggests that the limit of breathing comfort is reached when the external work exceeds [0.5 + 0.02 x (pulmonary ventilation)] Joule per litre of pulmonary ventilation.

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3.2 In practice the resistance to respiration imposed by an aircraft breathing system is defined in terms of the relationships between the pressure in the cavity of the mask and the corresponding respiratory demands. It is generally most appropriate to relate the minimum and maximum mask pressures during the respiratory cycle to the corresponding peak inspiratory and expiratory flows demanded by the wearer. It is normal practice to describe the resistance imposed by aircrew breathing equipment in terms of the total change of pressure in the mask cavity [the pressure swing] and the minimum and maximum mask pressures which are produced by equal inspiratory and expiratory flows. The pressure in the mask cavity averaged over the whole of the respiratory cycle is also a valuable expression of the performance of a breathing gas system, as this quantity determines in part the stresses imposed on the heart and circulation by the equipment.

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Total change of mask pressure

3.3 The total change (swing) of pressure in the mask cavity during the respiratory cycle (i.e. the difference between the minimum and maximum mask cavity pressures) should be as low as possible. The greater the swing, the greater is the sensation of resistance to breathing and the greater is the likelihood of incidents of hyperventilation, particularly in situations of high mental workload. The current standard for the maximum permissible change of mask cavity pressure during the respiratory cycle (with equal peak inspiratory and expiratory flow rates) is presented in Table 2. This standard ensures breathing comfort at pulmonary ventilations between 5 and 50 L (ATPD) min^{-1}. Although internal airway resistance is reduced at altitude, the effect on the total work of breathing is relatively small and it is present practice to require the resistance to breathing imposed by an aircrew breathing system to be within the same maximum limits at all altitudes from ground level to 38,000 feet, above which altitude pressure breathing is operative.

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Peak Inspiratory and Expiratory Flow Rates (L (ATPD) s^{-1})	**Maximum Acceptable Change of Mask Cavity Pressure during the Respiratory Cycle (kPa)**
0.5	0.5
1.5	0.85
2.5	1.75
3.3	3.0

Table 2. The maximum acceptable change of pressure in the mask cavity during the respiratory cycle at altitudes between ground level and a pressure altitude of 38,000 feet.

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of Mask Cavity Pressure during¶
the Respiratory Cycle (kPa)¶
0.5 0.5¶
1.5 0.85¶
2.5 1.75¶
3.3 3.0¶
**Table 2 - The Maximum Acceptable Change of Pressure in the Mask Cavity during the¶
Respiratory Cycle at Altitudes between Ground Level and 38,000 feet.¶**

Safety Pressure

3.4 The design of an oro-nasal mask and its suspension system should be such that a good seal between the edge of the mask and the face is maintained under all conditions of flight. The standard of this seal should be such that the inboard leakage of ambient air into the mask cavity does not exceed 5% of the pulmonary ventilation when the mean pressure in the mask cavity is between 0 and 1 kPa less than that of the environment. There are, however, situations in which this level of sealing of the mask to the face may not be achieved. Indeed a serious disadvantage of suction demand breathing systems in practice is that hypoxia can occur at altitude due to the inspiration of air through a leak between the mask and the face. Safety pressure which is the maintenance of the pressure in the mask cavity during inspiration at a value greater than that of the environment is widely employed in aircrew breathing systems to prevent the flow of environmental gas into the mask when there is a failure of the seal of the mask to the face. The ingress of air, toxic fumes or NBC warfare agents through a leak between the mask and the face could have serious consequences. In large aircraft, the requirement to provide effective denitrogenation by pre-breathing 100% oxygen to limit the risk of decompression sickness is also highly dependent on safety pressure. As long as the pressure in the mask cavity remains greater than that of the environment, then a failure of the seal of the mask to the face will result in a flow of breathing gas from the mask to the environment thus preventing the contamination of the breathing gas in the mask by air or toxic materials in the air. Although it is desirable that safety pressure is maintained in the mask cavity even at high inspiratory flow rates and in the presence of large leaks, the pressure-flow characteristics of most breathing gas delivery systems, in which the mask pressure falls with increasing flow, and the compensation of the expiratory valve, make this goal difficult, if not impossible, to meet. In such systems, a high safety pressure will be associated with a high resistance to expiration. A mean pressure in the mask cavity of +0.5kPa will, however, minimise the total work of breathing and increase breathing comfort.

3.5 The fraction of the inspired gas which enters a mask through a typical mask leak in a suction demand system is greatest at low inspiratory flows. The ratio of flow through the leak to total inspiratory flow falls rapidly as the latter rises. The presence of safety pressure is therefore most important during quiet breathing. It is thus possible to strike a compromise between the maximum inspiratory flow rate at which safety pressure is required to be present and the rise in mask expiratory pressure produced by the safety pressure. The UK standard requires safety pressure to be present in aircrew breathing systems at inspiratory flows of up to at least 1.2L (ATPD) s^{-1} and limits the maximum mask pressures during expiration to the values presented in Table 3 (Section B - safety pressure present). The minimum mask pressures allowed when safety pressure is present are also presented in Table 3. These limits to the peak mask pressures when safety pressure is present ensure that the effects of the associated increase of mean lung pressure of +0.25 to +0.5 kPa upon the circulation and distribution of body fluids are minimal and acceptable for many hours.

Peak Inspiratory and Expiratory Flows (L (ATPD) s^{-1})	**Acceptable Mask Cavity Pressures (kPa)**	
	Minimum	Maximum
A. Safety Pressure Absent		
0.5	-0.38	+0.38
1.5	-0.55	+0.65
2.5	-1.12	+1.00
3.3	-1.90	+1.50
B. Safety Pressure Present		
0.5	+0.02	+0.75
1.5	-0.20	+0.95
2.5	-0.90	+1.25
3.3	-1.75	+1.65

Table 3. The minimum and maximum acceptable mask cavity pressures during the respiratory cycle at altitudes between Ground Level and a pressure altitude of 38,000 feet.

3.6 In some aircraft breathing systems safety pressure is only operative at altitudes above either 10,000-15,000 feet or 30,000 feet. Below these altitudes, gas only flows from the regulator when the pressure in the mask is reduced below that of the environment. The reduction of mask pressure which occurs during inspiration in these circumstances should not give rise to the sensation of excessive inspiratory resistance. The suction in the mask cavity is not to exceed the values specified in Table 3 for the absence of safety pressure (section A). The maximum mask pressures which occur when safety pressure is not operative should be such that there is no sensation of excessive expiratory resistance. The maximum acceptable values are specified in Table 3 (Section A - safety pressure absent).

Further Increases of Mask Pressure

3.7 In use, certain routine and emergency conditions tend to raise the pressure in the mask cavity above the values seen during breathing in the steady state. Thus, in a typical pressure demand system in which the outlet valve of the mask is compensated to the pressure in the inlet hose of the

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Pressures (kPa) Minimum Maximum¶
A. Safety Pressure Absent¶
0.5 -0.38 +0.38¶
1.5 -0.55 +0.65¶
2.5 -1.12 +1.00¶
3.3 -1.90 +1.50¶
B. Safety Pressure Present¶
0.5 +0.02 +0.75¶
1.5 -0.20 +0.95¶
2.5 -0.90 +1.25¶
3.3 -1.75 +1.65¶
Table 3 - The Minimum and Maximum Acceptable Mask Cavity Pressures during the Respiratory Cycle at Altitudes between Ground Level and 38,000 feet.¶

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mask, head movement increases the pressure in the mask hose and hence the resistance to expiration and similarly a rise of mask hose pressure produced by a rapid ascent also increases expiratory resistance. In order to maintain breathing comfort, the rise of mask cavity pressure induced by realistic head movements or by the maximum rate of ascent of cabin altitude (with the cabin pressurised) is not to exceed 0.25 kPa. A continuous flow failure of the demand valve in a conventional compensated mask outlet valve system will result in a continuous rise of mask pressure. If the flow through the demand valve is relatively low, the wearer will experience expiratory difficulty. A high continuous flow will produce a rapid rise of mask and lung pressures, provided that the seal of the mask to the face is maintained. Inflation of the lungs to an intrapulmonary pressure of 10.7-13.3 kPag will, if the expiratory muscles are relaxed, result in overdistension of the lung tissue, rupture of the walls of air sacs and the passage of gas into the lung tissue, into the tissues within the chest and neck, into the pleural space (producing lung collapse) and most seriously into the ruptured pulmonary capillaries, allowing bubbles of gas into the heart and arterial vessels with a high probability of blocking arteries supplying parts of the brain which may cause unconsciousness and death. The rise of mask pressure produced by a high continuous flow failure of a demand valve must not exceed 5.5 kPa.

Venting of lungs on rapid decompression

3.8 Rapid decompression of the pressure cabin of an aircraft produces an almost equally rapid expansion of the gases in the lungs and airways and can produce over-inflation of the lungs with damage to the lung tissue with the consequences discussed in paragraph 3.7. The incidence and severity of the damage to the lungs produced by rapid decompression are determined primarily by the ratio of cabin pressure before the decompression to that after the decompression, the speed of the decompression (the reciprocal of the time constant of the decompression), the degree of opening the glottis (the orifice between the vocal chords) and the resistance to the flow of gas from the respiratory tract imposed by the breathing equipment. The breathing equipment worn by aircrew should allow free venting of the expanding gases from the lungs in these circumstances. The peak pressure difference between the gas in the lungs and the environmental pressure produced by a rapid decompression should not exceed the 10.6 - 13.3 kPag required to produce pulmonary damage by over-inflation of the relaxed chest. Present standards for aircrew breathing equipment require that the mask pressure on a rapid decompression to a final altitude of 38,000 feet (above this altitude pressure breathing is operative) in 0.1 seconds shall not exceed 5.5 kPag. This limit is somewhat arbitrary. It is one half of the intrapulmonary pressure required to damage the lungs by over-distension of the relaxed chest. There is some experimental evidence that short duration (<50 ms) peak mask pressures of up to 13.3 kPag on rapid decompression over a 35 kPa pressure change in 0.2 seconds will not cause lung damage. The probability of lung damage on rapid decompression is reduced if over-distension of the lungs is prevented by the application of counter pressure to the chest wall and abdomen during the decompression.

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Oscillatory activity

3.9 Aircrew breathing systems can exhibit oscillatory activity which produces oscillations of pressure in the mask, usually during inspiration. Such oscillations of mask pressure, particularly if they are of sufficient amplitude, are subjectively disturbing, may induce hyperventilation and can interfere with communication. The incidence, amplitude and frequency of these oscillations are determined by the oscillatory mechanics of the breathing equipment, by the impedance of the respiratory tract [when present, oscillatory activity is frequently much greater when the wearer breathes through the nose as compared with breathing through the mouth] and the respiratory flow pattern. Ideally any oscillatory activity which occurs should not be detectable subjectively; it must not be disturbing. Thus the double amplitude of any oscillation of pressure in the mask cavity which persists for longer than 0.25 seconds should not exceed 0.06 kPa.

4 Composition of Inspired Gas

4.1 Several physiological factors influence the requirements for the composition of the gas delivered to the respiratory tract. It is convenient to consider these requirements in terms of the limits to the concentration of oxygen in relation to cabin altitude. In conventional oxygen systems the diluting gas is virtually entirely nitrogen since the oxygen from the aircraft store is diluted with cabin air. The performance of molecular sieve oxygen concentrators is such that the product gas contains argon as well as oxygen and nitrogen. The maximum concentration of argon in the product gas is 5-6%. In this context argon has no specific physiological effects and can be regarded solely as an inert diluents gas. The concentration of oxygen in the gas delivered by a breathing system to the nose and mouth not infrequently fluctuates during a single breath (especially in continuous flow oxygen systems) and from one breath to another (as occurs in some molecular sieve oxygen concentrator systems). The physiological requirements with respect to the concentration of oxygen in the inspired gas discussed in the following paragraphs assume that the inspired gas is thoroughly mixed before it enters the respiratory tract. In mechanical testing the mean volume weighed concentration of oxygen in the gas delivered to the mask cavity should be determined by passing the gas from the expiratory port of the mask through a mixing box fitted with baffle plates and measuring the concentration of oxygen in the mixed gas flowing from the box. The final definitive measure of the “effective” concentration of oxygen delivered by a breathing system is the measurement of the alveolar PO_2 in human subjects breathing from the system during man rating. The composition of the alveolar gas may, with certain precautions, be determined in normal healthy subjects by measuring the PO_2 and PCO_2 of the gas flowing from the nose and mouth towards the end of expiration [the end-tidal PO_2 and PCO_2].

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4.2 The composition of the gas which enters the respiratory tract during inspiration when wearing breathing equipment depends not only on the composition of the gas delivered to the oro-nasal mask (or pressure helmet) through the inlet hose, but also on the proportion of the tidal volume which is gas which had been breathed out in the previous expiration. The re-breathing of previously expired gas adds external dead space to the respiratory tract and lowers the concentration of oxygen delivered to the alveolar gas. It also impairs the elimination of carbon dioxide from the body which raises the alveolar PCO_2 which in turn increases the pulmonary ventilation. The volume of the external dead space added by the oro-nasal mask (or pressure helmet) must therefore be minimised. Depending upon the shape of the cavity of the mask and the positioning of the inlet and outlet valves the effective respiratory dead space of a mask may be less than the volume of the mask cavity when the mask is sealed to the face of the wearer. The respiratory dead space added by most modern aircrew masks is of the order of 0.10-0.15L (ATPD). The maximum acceptable effective respiratory dead space of an oro-nasal mask or pressure helmet is 0.2L (ATPD).

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Minimum Concentration of Oxygen in the Steady State

4.3 The principal consideration is that the concentration of oxygen in the inspired gas shall be adequate to prevent significant hypoxia. The partial pressure of oxygen (PO_2) in the alveolar gas when breathing air at ground level (barometric pressure - 760 mmHg) is normally 103 +3 mmHg. The ability of a subject to respond rapidly to a novel situation is marginally impaired when the alveolar PO_2 is reduced to 75 mmHg by breathing air at a pressure altitude of 5,000 feet and significantly reduced when the alveolar PO_2 is reduced to below 60 mmHg by breathing air at pressure altitudes greater than 8,000 feet. When breathing equipment is worn throughout flight as by the aircrew of high performance combat aircraft, the concentration of oxygen in the inspired gas is to be such that the alveolar PO_2 is maintained at or above the value produced by breathing air at ground level, i.e. 103 mmHg. The alveolar PO_2 should never be allowed to fall below 75 mmHg [the alveolar PO_2 produced by breathing air at a pressure altitude of 5,000 feet] during normal flight with the cabin pressurised. The devices employed in molecular sieve oxygen concentrator systems to provide warning when the PO_2 of the product gas falls below an acceptable value have a significant tolerance band within which they may or may not provide a warning of a low PO_2. In

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order to ensure that adequate warning of impending hypoxia is given without spurious warnings, the minimum PO_2 of the product gas when the system is operating correctly should not be less than that required to maintain an alveolar PO_2 of 103 mmHg. The warning system shall always provide a warning when the PO_2 of the product gas falls below that required to maintain an alveolar PO_2 of 75 mmHg.

4.4 The concentration of oxygen required at a given altitude to produce a given alveolar PO_2 is calculated using the Alveolar Gas Equation with assumptions with respect to the partial pressure of carbon dioxide (PCO_2) in the alveolar gas and the respiratory exchange ratio, R. The Alveolar Gas Equation states that:

$$PA\,O_2 = (PI\,O_2 - PA\,CO_2\,[FI\,O_2 + (1-FI\,O_2)])/R$$

Where
$PA\,O_2 = P\,O_2$ in alveolar gas
$PI\,O_2 = P\,O_2$ in inspired gas saturated with water vapour at 37°C
$PA\,CO_2 = P\,CO_2$ in alveolar gas
$FI\,O_2$ = Fractional concentration of oxygen in the mixed dry inspired gas
R = Respiratory Exchange Ratio

The normal resting value of the alveolar PCO_2 is 40 mmHg and of R is 0.85. The concentration of oxygen required in the inspired gas and altitude to produce an alveolar PO_2 of 103 mmHg is presented in Figure 1. The concentration of oxygen required in the inspired gas to maintain an alveolar PO_2 of 103 mmHg rises to 100% at an altitude of 33,700 feet (barometer pressure = 190 mmHg). Above this altitude the alveolar PO_2 will fall below 103 mmHg even when 100% oxygen is breathed.

4.5 Breathing systems for aircrew whether in aircraft in which an oxygen mask is worn throughout flight or in an aircraft in which the aircrew don oxygen masks only when the cabin altitude exceeds 8,000 feet should provide the minimum concentration of oxygen in the inspired gas in relation to cabin altitude which will maintain an alveolar PO_2 of 103 mmHg [at cabin altitudes up to 33,700 feet]. Some degree of hypoxia is, however, acceptable in passengers in the emergency of loss of cabin pressure at altitude. European Aviation Safety Authority and US Federal Aviation Agency specifications for passenger oxygen systems allow the mean concentration of oxygen in the inspired gas to fall to a level which will produce an alveolar PO_2 of around 55 mmHg at pressure altitudes between 10,000 and 18,500 feet and an alveolar PO_2 of around 45 mmHg at pressure altitudes above 18,500 feet.

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R¶
Where¶
PAo2 = Po2 in alveolar gas¶
PIo2 = Po2 in inspired gas saturated with water vapour at 37°C¶
PAco2 = Pco2 in alveolar gas¶
FIo2 = Fractional concentration of oxygen in the mixed dry inspired gas¶
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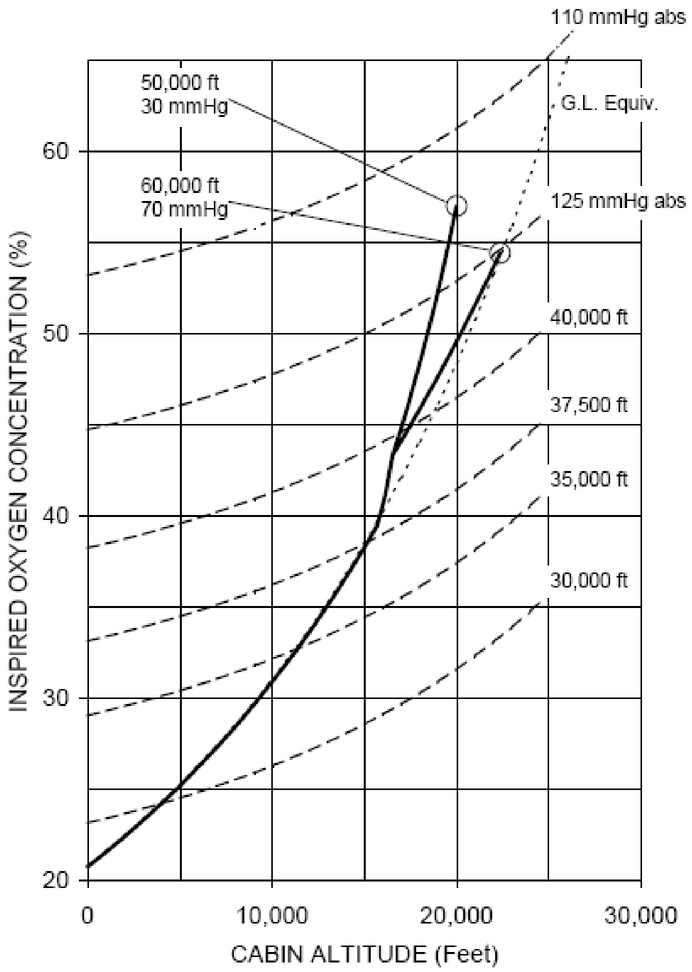

Figure 1. The relationships between the concentration of oxygen in the inspired gas and cabin altitude required (i) to maintain an alveolar Po2 of 103 mmHg - GL equivalent; (ii) to produce an alveolar PO_2 of 30 mmHg on rapid decompression to various final altitudes and intrapulmonary pressures - broken lines and (iii) to ensure rapid decompression of a 35 kPag pressure cabin will produce a minimum alveolar PO_2 of 30 mmHg when using two common pressure breathing schedules at pressure altitudes above 40,000 feet - solid lines.

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Minimum Concentration of Oxygen to prevent Hypoxia on Rapid Decompression

4.6 A second factor which influences the relationship between the concentration of oxygen in the inspired gas and cabin altitude is the need to prevent impairment of performance due to hypoxia following a failure of the pressure cabin at high altitude. When the inspired gas breathed before the decompression contains a significant concentration of nitrogen, the fall of the total pressure of the alveolar gas produced by rapid decompression produces a concomitant reduction of the alveolar PO_2, which may be to such a level that it produces impairment of performance or even

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unconsciousness. If the decompression is to a pressure altitude greater than 30,000 feet then 100% oxygen must be delivered to the respiratory tract immediately the decompression occurs if there is not to be a significant impairment of consciousness. There will be a significant impairment of performance if the alveolar PO_2 is reduced during the decompression to below 30 mmHg even for only a few seconds. If the magnitude of the area enclosed between an alveolar PO_2 of 30 mmHg above and the time course of alveolar PO_2 below exceeds 140 mm Hg.s then the individual will become unconscious. The decrement of performance at a choice reaction task is proportional to the magnitude of the area bordered above by a PO_2 of 30 mmHg and the time course of the alveolar PO_2 below. The breathing gas delivery system shall therefore prevent the alveolar PO_2 falling below 30 mmHg during and subsequent to a rapid decompression.

4.7 The major factors determining the minimum value of the alveolar PO_2 immediately after a rapid decompression are the initial and final absolute pressures of the alveolar gases, and the composition of the gases breathed before and after the decompression. Assuming that 100% oxygen is delivered to the respiratory tract immediately the decompression occurs, the alveolar PO_2 can be prevented from falling below 30 mmHg by ensuring that the gas breathed before the decompression contains an adequate concentration of oxygen and that the total intrapulmonary pressure does not fall below 115-120 mmHg (15.3-16 kPa) absolute. Assuming that the duration of the decompression is so short that there is no significant exchange of oxygen between the alveolar gas and the blood flowing through the lungs, then the alveolar PO_2 immediately after a decompression in which the absolute pressure of the lungs falls from PL(i) to PL(f) is related to the alveolar PO_2 immediately before the decompression by the equation:

Final alveolar PO_2 = (Initial alveolar PO_2 x (PL(f)-47)) / (PL(i)-47)

[all pressures expressed as mmHg]

4.8 This simple relationship may be employed to calculate the value of the alveolar PO_2 before the decompression which will produce an alveolar PO_2 of 30 mmHg immediately after the decompression from the initial to the final absolute pressures of the lung gas. The Alveolar Gas Equation (paragraph 4.4) can then be used to calculate the concentration of oxygen required in the inspired gas to ensure that the specified decompression will produce an alveolar PO_2 of 30 mmHg (but no lower) immediately after decompression. The concentrations of oxygen required in the inspired gas to produce an alveolar PO_2 of 30 mmHg immediately after a rapid decompression from a given initial cabin altitude to a given final cabin altitude [total absolute alveolar gas pressure at final cabin altitudes above 40,000 feet] are indicated by the interrupted curves of Figure 1. The relationship between initial cabin altitude and the final cabin altitude is determined by the pressurisation schedule of the cabin of the aircraft. The final alveolar gas pressure is also determined by the safety pressure/pressure breathing characteristics of the breathing gas delivery system. Thus the curve relating the minimum concentration of oxygen in the inspired gas to cabin altitude before a decompression required to prevent the alveolar PO_2 falling below 30 mmHg immediately after the decompression will depend upon the cabin pressurisation schedule of the aircraft and the safety pressure/pressure breathing characteristics of the breathing gas delivery system. In large aircraft a watch-keeping pilot is usually required to don and wear an oxygen mask on the flight deck when aircraft altitude is 40,000 feet or greater, to ensure appropriate oxygenation before decompression and timely provision of 100% oxygen.

4.9 The minimum inspired oxygen concentration-cabin altitude curves for two commonly used pressure breathing systems employed in aircraft with a cabin pressure differential of 35 kPa at aircraft altitudes above 23,000 feet are presented in Figure 1. Both of these pressure breathing systems commence pressure breathing at a cabin altitude of 40,000 feet and deliver oxygen at an absolute pressure which falls linearly with the reduction of environmental pressure at altitudes above 40,000 feet. One system employs a breathing pressure of 30 mmHg at 50,000 feet which provides an intrapulmonary pressure of 117.5 mmHg absolute at 50,000 feet. The other system

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employs a breathing pressure of 70 mmHg at 60,000 feet which provides an intrapulmonary pressure of 124 mmHg absolute at 60,000 feet. It may be seen from Figure 1 that the minimum concentration of oxygen required in the inspired gas to prevent significant hypoxia being induced by the rapid decompression is greater than that required to maintain an alveolar PO_2 of 103 mmHg in the steady state at cabin altitudes above 16,000 feet. The concentration of oxygen required in the inspired gas at cabin altitudes above 16,000 feet is greater with the pressure breathing system which employs a breathing pressure of 30 mmHg at 50,000 feet than the system which employs a breathing pressure of 70 mmHg at 60,000 feet. The minimum concentration of oxygen required in relation to cabin altitude to prevent hypoxia in the steady state and in the event of a rapid decompression in an aircraft with a 35 kPa differential pressure cabin and using a breathing pressure of 30 mmHg at 50,000 feet is summarised in Figure 2.

Maximum Concentration of Oxygen

4.10 Breathing high concentrations of oxygen during flight in high performance, combat aircraft has two important disadvantages. It results in acceleration atelectasis and delayed otitic barotrauma.

4.11 Exposure to sustained positive acceleration whilst breathing high concentrations of oxygen produces marked collapse of the lower part of the lungs due to the absorption of alveolar gas whilst the small sized airways are collapsed by the increased weight of the lungs. The symptoms of the condition are attacks of coughing accompanied often by a sense of difficulty of breathing or, less frequently, by discomfort in the chest. The coughing is usually provoked by an attempt to take a deep breath either in flight or, more frequently, on standing up in the cockpit after flight. The cough and difficulty in breathing may last a few moments or repeated attacks may occur over a period of 10 to 15 min. Field studies have shown that 80-85% of pilots develop the condition with symptoms in flights in which 100% oxygen is breathed and manoeuvres above +3 to 4Gz are performed. The lung collapse which often reduces the vital capacity by 40% is associated with a large right to left shunt (20-25% of the cardiac output) of venous blood flowing through the collapsed lung, which reduces the concentration of oxygen in the arterial blood. The collapse remains after the return to +1 Gz until the individual takes a deep breath and/or coughs.

4.12 The causative factors of acceleration atelectasis are exposure to accelerations greater than +3 to 4 Gz and breathing 100% oxygen. The degree of lung collapse and the intensity of the symptoms are greatly increased by inflation of the G trousers. The mechanism is absorption of gas from non-ventilated alveoli in the lower parts of the lungs. The ventilation of these alveoli ceases on exposure to +Gz acceleration as the increased weight of the lung above compresses the lower parts of the lung, closing the small and intermediate sized airways. Inflation of the abdominal bladder of the G trousers accentuates this process. A high concentration of nitrogen in the non-ventilated alveoli will maintain the patency of the latter whilst the increased accelerative force is operative and ventilation of the alveoli will recommence on return to +1 Gz. If, however, the gas breathed before the exposure to +Gz acceleration is 100% oxygen so that the concentration of nitrogen in the alveoli is very low, the blood flowing through the non-ventilated alveoli rapidly absorbs all the gas trapped in the alveoli and surface forces maintain the alveoli in the collapsed state after the return to +1 Gz until they are reopened by a deep inspiration and coughing. The rate of absorption of gas from nonventilated alveoli is increased sixty times when 100% oxygen is breathed instead of air before the cessation of ventilation of the lungs. The presence of a significant concentration of nitrogen which has a much lower solubility in blood than oxygen and carbon dioxide acts as a brake on the absorption of gas from the non-ventilated alveoli.

4.13 Although no long term deleterious effects have been found in aircrew who have had the condition repeatedly in flight, many air forces consider that the chest discomfort which is produced and the potential hazard to safety of coughing in flight make acceleration atelectasis unacceptable. Acceleration atelectasis is less likely to occur if the concentration of nitrogen in the gas breathed before and during the exposure to the sustained acceleration does not fall below 40%. In this

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context, the argon which is present in breathing gas produced by molecular sieve oxygen concentrators behaves as nitrogen as it is also relatively insoluble in blood. Laboratory studies suggest that the concentration of nitrogen required to prevent significant acceleration atelectasis at altitudes up to 25,000 feet is also 40%. Flight experience at cabin altitudes up to 20,000 feet confirms this finding.

4.14 Breathing 100% oxygen, especially if it is associated with ascent to and descent from even moderate altitudes, is followed in the vast majority of individuals by the development of ear discomfort and deafness (delayed otitic barotrauma). A typical picture is that, on waking from a night's sleep, following flights in which 100% oxygen has been breathed, the individual has discomfort in the ears and is moderately deaf. Breathing 100% oxygen results in the nitrogen normally present in the middle ear cavity being washed out and replaced by oxygen through the pharyngo-tympanic tube. In the absence of nitrogen or the presence of a high concentration of oxygen in the middle ear cavity the blood flowing through the wall of the cavity rapidly absorbs gas from the cavity. The absorption of gas reduces the pressure in the middle ear which draws the eardrum into the cavity causing discomfort and deafness. The reduction in pressure also draws fluid into the cavity. The process of absorption of gas from the middle ear can be slowed and arrested after flight by "clearing the ears" whilst breathing air. The re-introduction of nitrogen into the middle ear must be repeated several times over the 12-18 hours following a flight in which 100% oxygen is breathed if delayed otitic barotrauma is to be avoided. The use of 100% oxygen to reduce risk of decompression sickness during deliberate depressurised operations means that for certain mission profiles the occurrence of otitic barotrauma will be inevitable.

4.15 The incidence of delayed otitic barotrauma is reduced by the presence of a minimum concentration of nitrogen in the gas breathed during flight. The concentration of nitrogen required in the inspired gas to reduce the incidence and severity of this condition to negligible levels is between 40% and 50%. Laboratory evidence suggests that the incidence of delayed otitic barotrauma will be very low when the nitrogen concentration is between 30% and 40%.

4.16 The requirements to avoid acceleration atelectasis and delayed otitic barotrauma in flight set the limit to the maximum concentration of oxygen which should be present in the gas delivered to the respiratory tract by the breathing system of a high performance combat aircraft. This requirement can be met by ensuring that the maximum oxygen concentration does not exceed 60%. There are obvious limits to the maximum altitude up to which this requirement can be applied. Three factors play a part in deciding the range of cabin altitudes over which it should be applied. The first factor is cabin pressurisation schedule. Aircrew operating combat aircraft will only be exposed to cabin altitudes greater than 20,000-22,000 feet in the rare event of decompression of the cabin at high altitude when 100% oxygen must be breathed in order to prevent hypoxia. The second factor is the effect of high altitude upon the ability of the aircraft to sustain significant levels of acceleration. Some high performance combat aircraft are able to sustain high G at aircraft altitudes where the cabin altitude may be up to 22,000ft. The third factor which is relevant is that the design of the breathing system becomes more technically difficult and costs rise if the difference between the minimum and maximum allowable oxygen concentrations is very small. Such would be the case if the specification of performance required that the concentration of oxygen should not exceed 60% at cabin altitudes much above 15,000 feet. Taking all these factors into consideration, the compromise requirement in ASIC and NATO agreements is that the concentration of oxygen in the inspired gas delivered by the breathing system of an aircraft in which the aircrew will be exposed to sustained +Gz accelerations above +3 Gz should not exceed 60% at cabin altitudes up to 15,000 feet and 75% at a cabin altitude of 20,000 feet (Figure 2).

5 Pressure Breathing at Altitude

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5.1 The principal physiological hazards associated with loss of cabin pressure at pressure altitudes above 40,000 feet are hypoxia, decompression sickness and cold injury. A full pressure suit assembly is necessary if protection against all three hazards is required over a prolonged period. However, if the aircraft can descent promptly and rapidly (within 3-4 minutes) to an altitude of less than 40,000 feet, protection against hypoxia only is required. A full pressure suit assembly will provide the ideal physiological protection, but it is bulky, cumbersome, impairs operational efficiency during routine flying with an intact cabin, and imposes major ground procedural problems. Pressure breathing combined with partial pressure garments at altitudes in excess of 50,000 feet is used therefore to provide short term or "get-me-down" protection against hypoxia. Partial pressure garments are required to combat the undesirable physiological disturbances produced by pressure breathing, but in order to exploit the advantages of the partial pressure approach (less restriction when un-inflated and inflated, greater routine comfort and lower thermal load), it is desirable that the area of the surface of the body to which counter pressure is applied should be the minimum required to provide the specified protection. Thus the design of the counter pressure garments represents a compromise between ideal physiological requirements and functional convenience. In addition, since the protection against hypoxia using a partial pressure assembly is required for only a short period of time during emergency descent, some compromise in the level of alveolar PO_2 which is required is also acceptable. It is the interaction of the deleterious effects of hypoxia upon mental performance and the cardiovascular system, with the undesirable consequences of positive pressure breathing, which determine the acceptable minimum alveolar PO_2. Virtually all pressure breathing systems and partial pressure assemblies employ 100% oxygen in order to minimise the magnitude of the breathing pressure required at altitudes above 40,000 feet to maintain the required alveolar PO_2. The use of product gas from a molecular sieve oxygen concentrator comprising 5-6% argon and 94- 95% oxygen during pressure breathing at an altitude of 50,000 feet, requires the breathing pressure to be increased in order to maintain the alveolar PO_2 at the appropriate level. Pressure breathing with a pressure sealing mask and no counter pressure to the body is widely used to provide short duration protection against hypoxia on exposure to altitudes up to 48,000-50,000 feet. The mean mask cavity pressure required at 50,000 feet is a compromise between too high a pressure which will produce a faint, and too low a pressure which will not prevent a serious deterioration of performance due to hypoxia. The acceptable compromise is a mean mask pressure between 4.0 and 4.5kPag (30.0-33.8 mmHg) at 50,000 feet. Between 38,000 feet and 50,000 feet the mean mask pressure should increase linearly with fall of environmental pressure, the limits of mean mask pressure at 40,000 feet being +0.1 to 1.0 kPag (0.75-7.5 mmHg). During pressure breathing with a mask alone the total change of mask cavity pressure during the respiratory cycle should not exceed 0.5 kPa at peak inspiratory and expiratory flows of 0.5L (ATPD) s^{-1} and 1.0 kPa at peak inspiratory and expiratory flows of 1.83L (ATPD) s^{-1} [the absolute pressure in this context is the absolute pressure in the mask and respiratory tract].

5.2 The magnitude of the breathing pressure required to prevent unacceptable hypoxia at pressure altitudes above 50,000 feet requires the application of counter pressure to the chest and abdomen to support breathing and at higher altitudes counter pressure to at least a portion of the limbs to counteract the effects of the raised intrapulmonary pressure upon the cardiovascular system, and maintain an adequate arterial blood pressure and blood flow to the brain. Thus all partial pressure assemblies apply counter pressure to the external surface of the chest, most commonly by means of a bladder covering part or the entire chest and restrained within an outer inextensible fabric layer. The bladder is connected into the hose between the breathing gas demand regulator and the oro-nasal mask/pressure helmet so that it is inflated with breathing gas to the breathing pressure provided by the regulator. The bladder of the pressure jerkin not only applies counter pressure to the chest, but also to the whole of the abdomen which ensures the minimum of respiratory disturbances during pressure breathing. In some partial pressure assemblies counter pressure is applied to the abdomen and lower limbs by means of the G trousers which the crew member is primarily wearing to enhance tolerance of +Gz acceleration. The pressure in the G trousers during

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pressure breathing at altitude is raised to 1.5 to 3.2 times the breathing pressure. The optimum ratio of G trouser to breathing pressures varies with the degree of coverage provided by the G trousers and is about 2.0 when using the UK full coverage anti-G trousers.

5.3 A well-sealing oro-nasal mask can be used to deliver breathing pressures of up to 9.3 kPag (70 mmHg) for several minutes. A limited proportion of subjects can even tolerate pressure breathing with a mask at pressures up to 10.7 kPag (80 mmHg). The practical limit to the use of an oro-nasal mask without external support to the upper neck is a breathing pressure of 9.3 - 10.0 kPag (70-75 mmHg). The standard of sealing of a mask employed to deliver high pressures to the respiratory tract should be such that the outboard leakage from the mask when sealed to the face does not exceed 0.10 L (ATPD) s^{-1} at a mask pressure of 4 kPa and 0.25 L (ATPD) s^{-1} at a mask pressure of 9.3 kPa. If any leakage does occur during pressure breathing the fit of the mask should be adjusted so that the leaks do not occur into the eyes.

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5.4 Partial pressure assemblies which employ a partial pressure helmet to deliver 100% oxygen to the respiratory tract maintain the absolute pressure in the lungs at 18.7-20.0 kPa (141-150 mmHg) at all altitudes above 40,000 feet which, in the absence of hyperventilation, gives an alveolar PO_2 of 50-60 mmHg. The use of a breathing pressure of only 30 mmHg at 50,000 feet results in an intrapulmonary pressure of 117 mmHg (15.6 kPa) absolute and an alveolar PO_2 of 40 mmHg with a moderate degree of hyperventilation (alveolar PCO_2 = 30 mmHg). When pressure breathing is performed with an oro-nasal mask and counter pressure to the trunk and lower limbs at breathing pressures up to 70 mmHg (9.3 kPag) an intrapulmonary pressure of 130 mmHg (17.3 kPa) absolute produces mild to moderate impairment. Several current partial pressure assemblies comprising an oro-nasal mask with counter pressure to the trunk and lower limbs employ a breathing pressure of 70 mmHg (9.3 kPag) at an altitude of 60,000 feet, which provides an intrapulmonary pressure of 124 mmHg (16.5 kPa) absolute and an alveolar PO_2 of 45-50 mmHg. The relationship of breathing pressure (mask pressure) to altitude between 40,000 and 60,000 feet can take several forms (Figure 3). The mask pressure can be held at 141 mmHg (18.8 kPa) absolute with ascent above 40,000 feet until the breathing pressure reaches the maximum of 70 mmHg (9.3 kPag) [Figure 3 - solid line]. This relationship minimises the hypoxia at the intermediate altitudes. An alternative relationship is one in which the absolute pressure in the mask falls linearly with environmental pressure from 40,000 to 60,000 feet [Figure 3 - broken line]. This form of the relationship minimises the cardiovascular stress at the intermediate altitudes. The mask pressure averaged over the respiratory cycle during pressure breathing at altitudes over 40,000 feet is to be within 0.27 kPa of the nominal mask pressure. Partial pressure breathing systems employing an oro-nasal mask, trunk counter pressure (pressure waistcoat and G trousers or pressure jerkin) and G trousers can provide acceptable to aircrew at altitudes up to 60,000 feet. There is at present an insufficient body of evidence to support their use to provide protection at altitudes above 60,000 feet.

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5.5 The resistance to breathing during pressure breathing with respiratory counter pressure is determined by the relationships of the pressures in the mask cavity, the pressure applied to the chest by the respiratory counter pressure garment [which is generally assumed to be the pressure in the bladder, if a bladder system is used] and the pressure applied to the abdomen by the G trousers. The swings of pressure in the mask cavity and the chest counter pressure garment during pressure breathing with counter pressure should not exceed the limits specified in Table 2. The difference between the pressure in the mask cavity and the chest counter pressure garment shall at no time exceed 0.5 kPa.

5.6 The required intrapulmonary pressure must be established rapidly on a sudden decompression to high altitude if hypoxia is to be avoided. Thus on a rapid decompression (in 0.1 s) to an altitude above 45,000 feet the pressures in the mask cavity and in the respiratory counter pressure garment shall not fall below 120 mmHg (16 kPa absolute) for longer than 2 s. This standard determines the requirement for the rate of inflation of the respiratory counter pressure garment. In practice, however, where the garment will usually be inflated to safety pressure prior to a decompression, there is a need to vent excess gas from the garment to avoid over-pressurisation, although the latter can provide some protection against lung damage on a very rapid decompression.

6 Pressure Breathing for +Gz Protection

6.1 Pressure breathing for G protection (PBG) used in combination with anti-G trouser inflation is now a well established technique for raising the tolerance of +Gz acceleration. Pressure breathing together with extended cover G trousers can reduce the need for sustained G straining manoeuvres during exposures to +8 to +9Gz. Use of a chest counter pressure garment has not been demonstrated to provide any meaningful improvement in lung protection over the counter-pressure inherent in the acceleration forces acting on the chest wall, and is not a mandatory requirement for PBG (unlike pressure breathing for altitude). The pressure demand regulator provides pressure breathing in response to the rise in the pressure at the outlet of the anti-G valve. The latter typically controls the flow of cooled engine bleed air into and out of the G trousers. The anti-G valve inflates the G trousers rapidly (within 1-2 s) to the desired pressure in relation to the total applied +Gz. The relationship between pressure in the G trousers and applied G is trouser pressure rising linearly with acceleration from 0 at +2 Gz to 70 kPag at +9 Gz.

6.2 The optimum breathing pressure at +9 Gz is 60-65 mmHg (8.0-8.7 kPag). The preferred relationship is to commence pressure breathing at +4 Gz and for the breathing pressure to rise linearly to 60-65 mmHg (8.0-8.7kPag) at +9 Gz.

6.3 The resistance to breathing during pressure breathing with G should be minimal. The total swing of mask pressure should not exceed the limits specified in Table 2. Pressure breathing must not be operative unless the G trousers are pressurised as pressure breathing on exposure to +Gz acceleration without pressurisation of the G trousers will cause rapid loss of consciousness. The rise of pressure in the mask on the sudden application of +Gz must not lag more than 0.5s behind the rise of pressure in the G trousers, and the fall of pressure in the mask should not lag more than 0.5s behind the fall of pressure in the G trousers.

7 Pressure Breathing - Press-to-Test

7.1 A facility whereby pressure breathing may be obtained by the operation of a manual control is required to enable the user to test the standard of seal of the breathing gas delivery system up to and including the mask. The performance of this facility is to be such that the user can perform several respiratory cycles with the mask pressure raised.

7.2 The test pressure to be employed varies with the pressure breathing assembly in use. The mean mask pressure produced on press-to-test when a mask is worn alone should be within the limits +3.5 to +4.5 kPag. When chest counter pressure and G trousers are worn for protection on decompression at high altitude the facility should provide a mask pressure of 6.7 to 8 kPag and inflation of the G trousers to 1-2 times breathing pressure. This mask pressure is also to be provided in a press-to-test facility for a pressure breathing with G assembly. It should be noted that it is not acceptable to provide this facility simply by inflating the G trousers to the appropriate pressure, 62- 72 kPag, as the application of these G trouser pressures at +1 Gz gives rise to pain. The total change of mask cavity pressure during the operation of the press-to-test facility should not exceed 0.75 kPa at peak respiratory flows of 0.5L (ATPD) s^{-1} and 1.0 kPa at peak flows of 1.0L (ATPD) s^{-1}.

8 Protection against Hypoxia after Ejection

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breathing to a higher level of acceleration in order to minimise the incidence and severity of arm pain in cockpits where the hands are positioned below heart level.
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8.1 The delivery of breathing gas to the respiratory tract following ejection from an aircraft at altitude shall be such that significant hypoxia does not occur during the subsequent descent of the crew member to below 10,000 feet. Typical descent times from various altitudes to 10,000 feet are presented in Table 4.

A. Starting Altitude (feet)	B. Time to descent to 10,000 feet (second) Aircrew Alone	C. Time to descent to 10,000 feet (second) Aircrew in ejection seat* D.
H. 30,000	I. 70-110	J. 130
K. 40,000	L. 95-160	M. 170

Table 4 - Time to descend to 10,000 feet following ejection. * Ejection seat with 1.62 m diameter drogue.

8.2 The time taken to descend from altitudes up to 20,000-25,000 feet is such that breathing air throughout the whole of the descent will not cause significant impairment of performance. Thus it is not essential to provide supplemental oxygen for escape at altitudes up to 25,000 feet. Breathing gas with a PO_2 greater than 130-150 mmHg is required to prevent hypoxia on escape at altitudes above 25,000 feet. Pressure breathing is required at altitudes above 40,000 feet. Inward relief whereby the ejectee/parachutist can breathe ambient air in the event of either cessation of the breathing gas supply or separation from the ejection seat, is required. The headgear including the mask and its supply system must remain intact and remain in place during ejection and perform satisfactorily thereafter. The breathing equipment must perform satisfactorily at low temperature (-60°C) in the presence of representative air movement [at least 20 knots (37km.h^{-1})].

9 Provision of Inward Relief

9.1 The ability to breathe air is required in the event that the flow of breathing gas provided by the breathing equipment is inadequate to meet the inspiratory demand. This facility is necessary in order to avoid a sudden failure of the supply of breathing gas imposing a very high resistance to inspiration, a situation which could threaten flight safety. The inward relief facility must not allow the ambient air to dilute the breathing gas delivered by the breathing system during normal operation of the equipment and thereby cause hypoxia or allow toxic material in the cabin air to enter the breathing system. The crew member should be aware immediately that air is entering the breathing system. In many conventional breathing systems inward relief is obtained either by loosening the mask so that air can be inspired around it or by disconnecting the inlet hose of the mask from the supply system. Neither of these methods is satisfactory. Some systems employ a spring-loaded inward relief valve (anti-suffocation valve) in the wall of the mask or mask hose connector. The minimum suction required to open such an inward relief valve should be 1.25 - 1.75 kPag in order to ensure that the opening of the valve is noticed immediately by the wearer but that the inspiratory resistance is acceptable for breathing up to at least 30 minutes and it will not depress the respiration of an unconscious crewmember.

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in ejection seat*¶
20,000 40-60 70¶
30,000 70-110 130¶
40,000 95-160 170¶
50,000 110-190 215¶
60,000 130-220 245¶

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The relationships between the concentration of oxygen in the inspired gas and cabin altitude required (i) to maintain an alveolar Po2 of 103 mmHg - GL equivalent; (ii) to produce an alveolar Po2 of 30 mmHg on rapid decompression to various final altitudes and intrapulmonary pressures - broken lines and (iii) to ensure rapid decompression of a 35 kPag pressure cabin will produce a minimum alveolar Po2 of 30 mmHg when using two common pressure breathing schedules at altitudes above 40,000 feet - solid lines.¶

Figure 2. A specification embodying the physiological requirements for the relationship of the concentration of oxygen in the inspired gas and cabin altitude in the intact pressure cabin of a typical agile combat aircraft with a 35 kPag pressure cabin and a ceiling of 50,000 feet.

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Figure 3. Two acceptable forms of the relationship between mean mask pressure and altitude for a partial pressure assembly comprising a mask, pressure waistcoat or jerkin and G trousers. Note that both of these lines are nominal relationships - in practice, engineering tolerances would require that upper and lower limits be defined around either line (or any other acceptable line) based on aeromedical and engineering discussion.

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The instantaneous rates of flow of gas into and out of the respiratory system is one of the principal factors which determine the magnitude of the changes in mask pressure imposed by a breathing gas delivery system, the other being the pressure-flow characteristics of the breathing equipment itself. There is considerable variation in respiratory flow patterns between individuals, especially when breathing whilst at rest. Typically, the breathing frequency is 15 breaths a minute with each inspiration occupying 1.6 seconds and each expiration lasting 2.4 s. During inspiration the instantaneous flow rate typically rises rapidly to a maximum after 0.5 seconds and then falls at a slower rate to zero. Expiration usually follows the end of inspiration without a break. The instantaneous flow rate in expiration rises to reach a maximum which is somewhat less than the maximum attained in inspiration. The flow rate then declines slowly to reach zero at the end of this phase of the cycle. There is frequently a pause between the end of expiration and the commencement of the next inspiration. Of particular significance to the design of aircraft breathing systems are the maximum (peak) inspiratory and expiratory flow rates which occur during the respiratory cycle. Although for some purposes the instantaneous respiratory flow can be simulated by a sine wave (when the peak flow rate equals 3.14 times the pulmonary ventilation) the peak inspiratory flow rate at rest is typically 3.2-3.8 times the pulmonary ventilation whilst the peak expiratory flow rate is about 2.7 - 3.0 times the pulmonary ventilation. Respiratory flow patterns tend to become more regular as the pulmonary ventilation is increased by physical exercise. Inspiratory and expiratory times become more equal as do peak inspiratory and expiratory flow rates. Moderate increases of pulmonary ventilation produced by physical exercise typically occur by an increase in the size of individual breaths (i.e. increase of tidal volume) rather than an increase in the frequency of breathing. When the respiratory frequency increases it principally occurs by a shortening of the duration of expiration; the duration of inspiration only decreases slightly with increasing frequency of breathing.

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, generally hypoventilation but on occasions hyperventilation

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