Prevention of Hypoxia by a Continuous Flow of Product Gas

John Ernsting and Claire Peckover
Human Physiology and Aerospace Medicine
GKT School of Biomedical Sciences
King's College London

INTRODUCTION

Aircraft oxygen systems employing a continuous flow of oxygen with or without a reservoir have been employed widely in aviation for over a hundred years. These systems included the simple pipestem held in the mouth used by Tissandier and his colleagues in the ill fated balloon, the Zenith, in 1875, and by combat pilots in World War I and the loose-fitting mask into which oxygen flowed continuously, which were worn by pilots in the first two decades of the last century. The more sophisticated continuous flow system with a non-rebreathing reservoir developed by Haldane in 1916 for the clinical administration of oxygen was also used in flight. The United States Army Air Corps in World War II extensively used the rebreathing reservoir mask developed by Boothby and his colleagues at the Mayo Clinic in 1938. The continuous flow oxygen sets developed as an emergency supply system in World War II for use both in flight and on bale out from the aircraft in which the flow of oxygen is carried directly into the mask is still in use in many combat aircraft. Subsequent to the widespread adoption of demand regulators in military aircraft in the fourth and fifth decades of the twentieth century a continuous flow by-pass facility was introduced into several demand regulators as a means of maintaining the supply of oxygen to the aviator following failure of the demand valve to pass oxygen. Recently, the provision of a continuous flow of the breathing gas from a molecular sieve oxygen concentrator (MSOC) has been used as a method of continuing to provide breathing gas in the event of a failure of the main demand regulator to pass gas in a high performance, low cabin differential pressure aircraft.

With a resurgence of the use of a continuous flow by-pass facility as a secondary method of maintaining the oxygenation of a crew member in the event of a failure of the demand valve of the main regulator to pass gas and the novel use of MSOC product gas instead of oxygen in the facility has led to a re-examination of this simple delivery system. This paper describes the development and use of a simple model of this system which has been employed to study the effects of relevant variables upon the composition of the gas delivered to the respiratory tract by the facility and the results of a validation study using human subjects and a continuous flow by-pass facility supplied with product gas from a MSOC.

CONTINUOUS FLOW BY-PASS FACILITY

A common arrangement of a continuous flow by-pass facility in a modern pressure demand oxygen regulator employing product gas from a MSOC comprises an on/off valve whereby the supply of product gas to the by-pass facility is controlled and an orifice which regulates the flow of product gas into the low pressure outlet of the regulator. Thus when by-pass is selected a continuous flow of product gas is fed into the outlet of the regulator. This flow of product gas passes through the hoses and connectors between the outlet of the regulator and the inlet port of the oronasal mask into the mask cavity. The conventional inlet valve and compensated outlet valve of the mask are complemented by a third valve, a spring-loaded anti-suffocation valve through which ambient air can be drawn when the inspiratory effort of the wearer reduces the pressure in the mask cavity to 5.0-7.0 inch water gauge below that of the environment [Ernsting and Macmillan 1966]. The final component of the continuous by-pass facility is a relief valve whereby the product gas flowing through the metering orifice in the regulator can flow directly to ambient when the instantaneous inspiratory demand of the wearer is less than the volume flow of product gas into the mask. This relief is provided in modern pressure demand regulators by the spring-loaded and pressure compensated dump valve fitted at the outlet of the regulator, which prevents the pressure of the gas flowing from the regulator from exceeding certain limits typically, at cabin altitudes below 38,000 feet, a pressure slightly in excess of the safety pressure delivered by the demand regulator e.g. 3.5-4.0 inch water gauge.

The by-pass facility provides a continuous flow of product gas into the cavity of the mask during inspiration. Air enters the mask through the anti-suffocation valve whenever the instantaneous inspiratory flow of the wearer exceeds the volume flow of product gas. The mass flow of product gas from the by-pass facility is determined by the size of the metering orifice, and the absolute pressures of the product gas immediately upstream and downstream of the metering orifice. The pressures at which typical MSOC systems supply product gas to the orifice exceeds 15 Lb in^{-2} gauge at all altitudes in flight (except in situations such as idle descent) so that the mass flow of product gas through the by-pass orifice is independent of the pressure downstream of the orifice. The volume flow of product gas from the orifice into the mask will vary with the absolute pressure in the cabin (cabin altitude). The volume flows of gas provided by a typical by-pass facility [an orifice flow of 10.0 litre (NTP) min^{-1} at a supply pressure of 15.0 Lb in^{-2} gauge at ground level] at various supply pressures and cabin altitudes are presented in table 1.

THE MODEL

The model describes the mean concentration of oxygen in the inspired gas in terms of the nature and magnitude of the respiratory demand of the subject wearing the mask, the mass flow of product gas passed by the orifice, the concentration of oxygen in the product gas and the cabin altitude.

In order to simplify the stages of the development of the model it is assumed initially that the gas flowing through the orifice of the by-pass facility is 100% oxygen. The effects of the lower concentrations of oxygen in the product gas supplied by a MSOC are considered later in the description of the model.

Concentration of oxygen in the mixed inspired gas

Whenever the instantaneous inspiratory flow exceeds the volume flow of oxygen into the mask air will be drawn into the mask through the anti-suffocation valve and the instantaneous fractional concentration of oxygen (F_{O2}) in the mixture of oxygen and air in the gas entering the respiratory tract will be less than 1.0. Since the instantaneous flow of gas into the respiratory tract rises from O at the beginning of inspiration to a peak at about the middle of inspiration and then falls back to O at the end of inspiration, the instantaneous F_{O2} in the inspired gas will be high (1.0) at the beginning of inspiration, fall to a minimum at the instant at which the inspiratory flow peaks and then increase to a high value (1.0) at the end of this phase of the respiratory cycle. The effects of this pattern of variation of F_{O2} during inspiration upon the F_{O2} of the alveolar gas are complex and difficult to calculate. In the present model it has been assumed that the nett effect of such variations in F_{O2} on the alveolar F_{O2} will be identical to that produced by thorough mixing of the same quantities of oxygen and air before the gases enter the respiratory tract.

The F_{O2} of the mixed inspired gas in this system is critically dependent upon the volume oxygen flow, the respiratory flow pattern, the tidal volume and the respiratory frequency. The factors affecting the volume flow of oxygen into the mask have been discussed in a previous section. The pulmonary ventilation, and its components, tidal volume and respiratory frequency, are determined principally by the physical work being performed by the pilot and variations in the breathing pattern. In flight measurements of pulmonary ventilation of pilots performing simulated combat sorties (Harding 1987) have shown that the pulmonary ventilation of the pilot of a high performance aircraft varies between 5 and 50 litre (ATPD) min^{-1} with a grand mean value of 22 litre (ATPD) min^{-1}. Of interest in the present context is the highest pulmonary ventilation which occurs during the type of flight which a pilot would conduct following a failure of the demand valve and selection of the continuous flow bypass facility. The realistic maximum pulmonary ventilation in this situation is 30-35 litre (ATPD) min^{-1}.

The shape of the inspiratory flow pattern

For a given volume flow of oxygen and tidal volume the F_{O2} of the mixed inspired gas also depends on the respiratory flow pattern. The shape of the flow pattern varies from one breath to another, with the level of pulmonary ventilation and from one individual to another. A significant feature in the present context is the ratio of the duration of inspiration (T_I) to the total cycle time (T_T) as the oxygen that flows into the mask will only be drawn into the respiratory tract during inspiration. The ratio T_I/T_T typically varies from 0.4 at rest to 0.5 during exercise. Two important changes in the respiratory flow pattern which occur in flight in combat aircraft are those produced by speech and the anti-G straining manoeuvre (AGSM). Speech whilst having a minor effect on the tidal volume typically reduces the T_I/T_T ratio to 0.15-0.25 (Ernsting 1960). The breathing cycle employed in the AGSM of expiratory effort against a closed glottis for 3 sec followed by a respiratory cycle occupying about 1 sec typically reduces the ratio T_I/T_T to 0.13 (AGARD 1990). Values of the ratio T_I/T_T of 0.5 and 0.2 are employed in the illustrative calculations presented in the paper.

A sine wave has been used by many investigators to represent the respiratory flow pattern at rest and during exercise (Otis et al, 1950). A half-sine wave has been used in this paper to represent the typical inspiratory flow pattern. At one extreme the inspiratory flow pattern may approach a square wave (rectangular pattern). Speech and the AGSM which greatly reduce the ratio of inspiratory time to total cycle time, but do not reduce the tidal volume, produce a marked increase in the peak flow and the shape of the inspiratory flow pattern tends to become more triangular. Peak flows in speech are typically 100-200 litre (ATPD) min^{-1} (Ernsting, 1960) whilst peak flows of 150 to 260 litre (ATPD) min^{-1} are typical of inspiratory flow patterns during the AGSM (Gordge, 1993).

Effect of shape of inspiratory flow pattern

The gas entering the respiratory tract in a continuous flow by-pass system will comprise only 100% oxygen if the volume flow of oxygen into the mask is greater than the peak inspiratory flow. If the instantaneous inspiratory flow exceeds the volume flow of oxygen, then air entering through the anti-suffocation valve will dilute the latter. For a given shape of inspiratory flow pattern the proportion of the inspired tidal volume which is 100% oxygen is related in a constant manner to the oxygen flow expressed as a proportion of peak (maximum) inspiratory flow. This relationship is depicted in *figure 1* for the three shapes of inspiratory flow patterns described in the previous section namely rectangular, half-sine wave and triangular. A change in the inspiratory flow pattern from rectangular to half-sine wave increases the ratio of the volume of oxygen to the tidal volume at a given ratio of the oxygen flow to peak inspiratory flow. A change in the shape of the inspiratory flow curve from a half-sine wave to a triangle produces a further increase in the proportion of the volume of oxygen to the tidal volume at a given ratio of oxygen flow to peak inspiratory flow. The magnitude of this change is, however, considerably less than the effect of a change from a square wave to half-sine wave pattern (*figure 1*). It has been assumed in the present model that the shape of the inspiratory flow pattern is a half-sine wave.

Effect of ratio of duration of inspiration to total cycle time

If the volume flow of oxygen is less than the peak inspiratory flow then the F_{O2} of the mixed inspired gas will fall as the ratio of the duration of inspiration to the duration of the total respiratory cycle (T_I/T_T) decreases. The effect of variations in ratio T_I/T_T upon the F_{O2} of the mixed inspired gases has been investigated for a half-sine wave inspiratory flow pattern assuming that there is no change in the actual tidal volume and breathing frequency. As the ratio T_I/T_T departs from 0.5 there will be an apparent change in breathing frequency and minute volume which can be calculated assuming a symmetrical sine wave breathing pattern. The peak inspiratory flow corresponding to this apparent minute volume can then be determined using the relationship peak inspiratory flow equals 3.14 times the apparent minute volume. Knowing the oxygen flow the F_{O2} of the mixed inspired gas can then be calculated using the relationship for a half-sine wave inspiratory flow pattern presented in *figure 1*. The effect of variations of the ratio T_I/T_T upon the F_{O2} of the mixed inspired gas for a constant tidal volume of 1.0 litre, a constant respiratory frequency of 20 breaths min^{-1} and an oxygen flow of 20 litre min^{-1} is presented in *figure 2*. It can be seen that the reduction of T_I/T_4 from 0.5 to 0.2 associated with speech or the performance of the AGSM will, in this condition, reduce the F_{O2} of the mixed inspired gas from 0.58 to 0.38. This calculation emphasises the sensitivity the F_{O2} of the mixed inspired gas to the ratio of the duration of inspiration to total respiratory cycle time in simple continuous flow oxygen systems.

Prediction of inspired F_{O2} by the model – 100% oxygen

The model described in the previous sections has been used to investigate the effects on the performance of continuous flow by-pass systems providing 100% oxygen of pulmonary ventilation, altitude and the T_I/T_T ratio. In an illustrative study the mass flow of 100% oxygen was set at 10 litre (NTP) min^{-1} and the relationship between the F_{O2} of the mixed inspired gas and cabin altitudes calculated for three levels of pulmonary ventilation namely 10, 20 and 30 litre (ATPD) min^{-1} for half-sine wave inspirations with a T_I/T_T ratio of 0.5. The results of these calculations are presented in *figure 3*. Also plotted in *figure 3* is the relationship between the F_{O2} of the mixed inspired gas and cabin altitude required to maintain the partial pressure of oxygen (P_{O2}) in the alveolar gas equal to that produced by breathing air at sea level (sea level equivalent). It may be seen the mixed inspired F_{O2} rises progressively with increasing altitude, due to the expansion of the metered oxygen flow at altitude. The mixed inspired F_{O2} falls with increasing ventilation. The F_{O2} remains greater than the sea level equivalent at cabin altitudes up to 25,000 feet in the conditions specified for the study until the pulmonary ventilation exceeds 24 litre (ATPD) min^{-1}. When the pulmonary ventilation is raised to 30 litre (ATPD) min^{-1} the inspired F_{O2} is maintained greater than that required to provide a sea level equivalent at cabin altitudes up to 20,000 feet. The results of a similar set of calculations using the same conditions, except that the T_I/T_T ratio is 0.2, are presented in *figure 4*. A comparison of *figures 3* and *4* illustrates the large effect which reducing the T_I/T_T ratio has upon the F_{O2} of the mixed inspired gas. With the lower value of the ratio T_I/T_T the inspired F_{O2} falls below the sea level equivalent above a cabin altitude of 8,000 feet when the pulmonary ventilation is 30 litre (ATPD) min^{-1}. With a T_I/T_T ratio of 0.2 even at a pulmonary ventilation of 20 litre (ATPD) min^{-1} the alveolar P_{O2} provided by a metered oxygen flow of 10 litre (NTP) min^{-1} will fall below the normal value breathing air at sea level when the cabin altitude exceeds 12,500 feet (*figure 4*).

Prediction of inspired F_{O2} by the model – product gas

Of particular interest in the present context is the additional effect of the use of MSOC product gas in place of 100% oxygen. The very considerably lower F_{O2} in product gas will of course reduce the F_{O2} of the mixed inspired gas. The process of calculating the F_{O2} of the mixed inspired gas when product gas is employed is very similar to that presented for 100% oxygen in earlier sections of this paper. The mixed inspired gas is now a mixture of product gas with a F_{O2} less than 1.0 and air. The F_{O2} of the product gas will vary significantly with the type of MSOC and the cabin altitude. In the illustrative study presented in *figure 5* the limits of F_{O2} in the product gas have been taken from a typical MSOC system specification. Thus at the cabin altitude of 20,000 feet used in this study the F_{O2} of the product gas will be between 0.55 and 0.75. Whilst the variables considered and calculations performed in this study are similar to those used in the earlier studies presented in this paper the F_{O2} of the mixed inspired gas is plotted as a function of pulmonary ventilation. Curves have been calculated for typical limits of the concentration of oxygen in the product gas [55% and 75%] and two values of the ratio T_I/T_T namely 0.5 and 0.2. The flow of product gas in this study is 10 litre (NTP) min^{-1}. The inspired F_{O2} which will produce the alveolar P_{O2} associated with breathing air at ground level (alveolar P_{O2} = 103 mmHg) and 10,000 feet (alveolar P_{O2} = 55 mmHg) are also indicated in *figure 5*. With a T_I/T_T ratio of 0.5 the highest product gas F_{O2} under the conditions of this study will only maintain at sea level equivalent alveolar P_{O2} at pulmonary ventilations up to 23 litre (ATPD) min^{-1}. A reduction of the F_{O2} of the product gas to the minimum specified at a cabin altitude of 20,000 feet (0.55) and will produce a mixed inspired F_{O2} which is less than that required to produce a sea level equivalent even at a low pulmonary ventilation of 10 litre (ATPD) min^{-1}. The reduction of the T_I/T_T ratio to 0.2 produced by speech and the AGSM will produce significant hypoxia at moderate levels of pulmonary ventilation when the concentration of oxygen in the product gas is at the lower limit of 55%. A product gas flow considerably greater than 10 litre (NTP) min^{-1} is required to maintain an adequate F_{O2} in the mixed inspired gas especially when the F_{O2} of the product gas is towards the lower limit.

EXPERIMENTAL VALIDATION OF THE MODEL

The opportunity was taken during the assessment of the performance using human subjects of a MSOC system developed by Normalair-Garrett Ltd (Honeywell) and which included a continuous flow by-pass facility in the pressure demand regulator to investigate the predictive value of the model described in the previous sections of their paper.

Methods

The MSOC system was installed in two compartments of a multi compartment hypobaric chamber with one chamber representing the aircraft pressure environment and the other the cabin environment. The MSOC which was mounted in aircraft compartment was supplied with clean air at pressures of 25 and 40 Lb in^{-2} relative to the absolute pressure in the "aircraft" compartment. Product gas was fed to the ejection seat mounted components of the MSOC system which were located in the pressurised cabin. The outlet of the regulator assembly was connected through a personal equipment connector and low-pressure hose and connector to a standard type P/Q mask fitted with an anti-suffocation valve. A mask mounting plate was secured to the facepiece of this mask. The pipe secured to the mask mounting plate was connected through a heated Fleisch capillary flowmeter and a short length of flexible hose to the cavity of an oronasal mask worn by the subject. This arrangement allowed the continuous recording of respiratory flow demands. The volume of the dead space added to the breathing system by this arrangement was of the order of 100 ml.

The subject was seated on a cycle ergometer so that he could exercise at various work rates up to 100W in order to produce the required levels of pulmonary ventilation. In addition to the instantaneous respiratory flow and pulmonary ventilation recorded by means of the capillary flowmeter mounted between the masks, the concentrations of oxygen and carbon dioxide in the gas flowing through the cavity of the mask worn by the subject were recorded continuously using a respiratory mass spectrometer. The pressure in the cavity of the type P/Q mask was also recorded continuously by means of a pressure transducer as was the pressure in the mask tube. The concentrations of oxygen in the product gas supplied to the regulator assembly by the MSOC were recorded using a rapid response oxygen analyser.

Six subjects participated in the study, which was conducted at cabin altitudes between 0 and 25,000 feet. The subject breathed "normally" from the system with the continuous flow by-pass facility selected and no flow of gas through the demand valve of the regulator at each altitude and exercise level until the end-tidal concentrations of oxygen (F_{O2}) and carbon dioxide (F_{CO2}) had been constant for one minute. The procedure was performed at the two air supply pressures to the MSOC (25 and 40 Lb in^{-2}g). On occasions, having achieved a respiratory steady state at rest or during exercise, the subject spoke, reading aloud a passage from an article. In these circumstances the end-tidal gas concentrations were carefully monitored to ensure that the end-tidal P_{O2} did not fall below 50 mmHg.

Results

The records of the F_{O2} in the mask cavity during inspiration demonstrated clearly that the $F_{O2\ of}$ the gas entering the respiratory tract fluctuated considerably during a single breath. The mean FO2 of the inspired gas in each condition was therefore calculated from the measured end-tidal F_{O2} and F_{CO2} using the alveolar gas equation (Ernsting 1999). The value was the respiratory exchange ratio was predicted from the recorded level of pulmonary ventilation using the relationship established in mild and moderate steady state exercise.

The inspired F_{O2} calculated from the experimentally determined end-tidal F_{O2} and F_{CO2} for each experimental condition was then compared with the F_{O2} of the F_{O2} of the mixed inspired gas calculated using the model. The values which were inserted into the model for each condition were:

(i) the volume flow of product gas calculated from the known pressure flow characteristic of the by-pass orifice and the measured pressure at which product gas was supplied to it, and the cabin altitude.

(ii) the F_{O2} of the product gas determined from the record of this variable.

(iii) the inspiratory minute volume demanded by the subject from the record of integrated inspiratory flow.

It was assumed that the inspiratory flow pattern was a half-sine wave and that the T_I/T_T ratio was 0.5.

The comparison of the measured F_{IO2} and the predicted F_{IO2} for each steady state condition with "normal" breathing at rest and during exercise with pulmonary ventilations up to 45 litre (ATPD)/min^{-1} is presented in *figure 6*. The line of identity of measured and predicted values is also given. It can be seen that there is good agreement between the value of F_{O2} predicted by the model and the directly measured values of F_{O2}. The latter tend to be slightly greater than the former by an average of 3% oxygen concentration. This very slight bias may be due to the delivery gas containing high F_{O2} in the early part of inspiration or to the method employed to allow all the relevant respiratory variables to be recorded during the measurements of the performance of the continuous flow by-pass system. The degree of agreement between predicted and measured values presented in *figure 6* suggests that the model described in an earlier section of this paper provides a good prediction of the F_{O2} of the mixed inspired gases in this continuous flow system.

Speech

The change in inspiratory flow pattern associated with speech produced a significant reduction in the end-tidal F_{O2}. The end-tidal F_{O2} fell progressively with each breath over 40 seconds of speech (*figure 7*). The investigator in most of the experimental conditions terminated the period of speech as the end-tidal P_{O2} fell below 50-60 mmHg. The length of time for which the subject spoke aloud before the end-tidal P_{O2} fell below 75 mmHg (the alveolar P_{O2} produced by breathing air at an altitude of 5,000 feet) varied between 15 and 50 sec depending upon the pulmonary ventilation, the F_{O2} and volume flow of the product gas, and the cabin altitude. Although with speech the F_{O2} of the mixed inspired gas would have fallen eventually to a relatively constant lower value the rate of fall of the end-tidal F_{O2} (and alveolar F_{O2}) was due to the effect of the volume of gas in the lungs (typically 3 litre) which “buffers” sudden changes in the composition of the inspired gas. A constant end-tidal F_{O2} was only achieved during speech at altitude when the subject was at rest. In all other situations the subject was instructed to stop speaking and resume a normal breathing pattern as the end-tidal P_{O2} fell below 50-60 mm Hg.

These results confirmed the very significant effect that the reduction in the T_I/T_T ratio produced by speech had upon the F_{O2} of the mixed inspired gas. They strongly confirm the conclusions drawn as a result of the studies conducted using the model of continuous flow by-pass systems that speech markedly reduces the F_{O2} of the mixed inspired gas. The low value of the T_I/T_T ratio associated with performance of the AGSM will produce a similar reduction in the F_{O2} of the mixed inspired gas. Aircrew who may employ a continuous flow by-pass system in flight should be warned of this phenomenon, the intensity and significance of which will vary with the volume flow and F_{O2} of the product gas provided by the continuous flow by-pass.

SUMMARY

A simple model for calculating the concentration of oxygen in the mixed inspired gas provided by a continuous flow by-pass system using a mask mounted air inlet (anti-suffocation) valve and employing the gas produced by a molecular sieve oxygen concentrator is described. The variables considered in the model relate to the by-pass system, the aircraft and the breathing of the aviator. The variables in the continuous flow by-pass system are the characteristics of the metering orifice of the by-pass facility and the pressure and concentration of oxygen in the product gas supplied to the orifice. The model considers the aircraft and cabin altitudes. Finally, the respiratory demand of the aviator, specifically the shape of the inspiratory flow pattern, the ratio of the duration of inspiration to the total respiratory cycle time, the tidal volume and breathing frequency (hence pulmonary ventilation) are considered as variables. The paper presents examples of such calculations of the oxygen concentration in the inspired gas using a typical mass flow through the metering orifice (10 litre (NTP) min^{-1}) of 100% oxygen and of product gas. The effect of changes in the various variables are explored and discussed.

The conduct and results of a validation study in which human subjects were provided with breathing gas through the continuous flow by-pass facility of an onboard oxygen generating system are presented. The subjects performed exercise on a cycle ergometer to increase pulmonary ventilation and were exposed to cabin altitudes up to 25,000 feet in a hypobaric chamber. The subjects also read aloud to investigate the effects of speech on the delivery of oxygen to the respiratory tract. The oxygen concentration in the inspired gas in each experimental condition was determined from the recorded end-tidal concentrations of oxygen and carbon dioxide. The directly measured oxygen concentrations in the inspired gas agreed closely with the values predicted by the model. It is considered that the model described in this report provide a reliable estimate of the oxygen delivery performance of a simple continuous flow system.

The study using human subjects also confirmed the predicted decrease of the alveolar partial pressure of oxygen induced by speech and which would be produced by the anti-G straining manoeuvre. These changes in the breathing pattern should be limited to very short periods (less than 10-15 sec) when a continuous flow by-pass system is in use.

Acknowledgement

The studies using human subjects were conducted in the hypobaric facilities at Normalair-Garrett Ltd (Honeywell). The authors wish to thank the staff at Normalair-Garrett Ltd for their unstinting help and support during the studies, especially those who volunteered to act as subjects.

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Captions to Figures

Figure 1**.** The relationships, in a system employing a metered flow of gas and an inlet valve which adds air when the instantaneous inspiratory flow exceeds the flow of metered gas, between the ratio of the flow of the metered gas to the peak inspiratory flow *and* the volume of the metered gas inspired as a proportion of the tidal volume. The relationships are shown for three shapes of inspiratory flow pattern – rectangular, half-sine wave and triangular.

Figure 2. The effect of the ratio of inspiratory time to total cycle time upon the fractional concentration of oxygen in the mixed inspired gas when the tidal volume is 1.0 litre (ATPD), breathing frequency is 20 bpm and the metered oxygen volume flow is 20 litre (ATPD) min^{-1}.

Figure 3. The relationship between the fractional concentration of oxygen in the mixed inspired gas and cabin altitude with a metered oxygen flow of 10 litre (NTP) min^{-1} at three levels of pulmonary ventilation (10, 20 and 30 litre (ATPD) min^{-1}) and a ratio of inspiratory time to total cycle time of 0.5. The broken line indicates the concentration of oxygen in the inspired gas required to maintain an alveolar oxygen tension of 103 mmHg.

Figure 4. The relationship between the fractional concentration of oxygen in the mixed inspired gas and cabin altitude with a metered oxygen flow of 10 litre (NTP) min^{-1} at three levels of pulmonary ventilation (10, 20 and 30 litre (ATPD) min^{-1}) and a ratio of inspiratory time to total cycle time of 0.2. The broken line indicates the concentration of oxygen in the inspired gas required to maintain an alveolar oxygen tension of 103 mmHg.

Figure 5. The relationships between the fractional concentration of oxygen in the mixed inspired gas and pulmonary ventilation at a cabin altitude of 20,000 feet with a metered flow of product gas of 10 litre (NTP) min^{-1} containing either 55% or 75% oxygen. The relationships have been calculated for ratios of inspiratory time to total cycle time of 0.5 and 0.2. The horizontal lines represent the concentrations of oxygen in the inspired gas required to provide alveolar oxygen tensions of 103 mmHg (sea level equivalent) or 54 mmHg (10,000 feet equivalent).

Figure 6. Comparison of the results of direct measurement from the end-tidal gas tension of subjects at rest and exercise of the oxygen concentration in the inspired gas and that predicted by the model described in the text.

Figure 7. The effect of speech (reading aloud) on the end-tidal concentration of oxygen in a subject exercising on a cycle ergometer at 25,000 feet and breathing a metered flow of product gas containing 90% oxygen. The period of speech is indicated by the rectangular box.

Table 1 The volume flow of product gas at altitude and at two product gas pressures (25 and 40 Lb in^{-2} gauge relative to aircraft altitude) provided by a metering orifice passing a flow of 10 litre (NTP) min^{-1} at a supply pressure of 15.0 Lb in^{-2} gauge at ground level.

Cabin Altitude (feet)	***Product Gas Pressure (Lb in^{-2} abs)***	***Product Gas Flow (litre (ATPD) min^{-1})***
0	40	13.3
	55	18.3
10,000	35	17.0
	50	24.3
15,000	33.3	19.7
	48.2	28.5
20,000	31.8	23.1
	46.8	34.0
25,000	30.5	27.4
	45.5	40.9