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N00014-83-K-0019

A THEORETICAL METHOD FOR SELECTING  
SPACE CRAFT AND SPACE SUIT ATMOSPHERES

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ABSTRACT

A theoretical method for selecting space craft and space suit atmospheres is described. The method assumes that gas bubbles cause decompression sickness and that the risk increases when a critical bubble volume is exceeded. The method is consistent with empirical decompression exposures for humans under conditions of nitrogen equilibrium between the lungs and tissues. Space station atmospheres are selected so that flight crews may decompress immediately from sealevel to station pressure without preoxygenation. Bubbles form as a result of this decompression but are less than the critical volume. The bubbles are absorbed during an equilibration period after which immediate transition to suit pressure is possible. Exercise after decompression and incomplete nitrogen equilibrium are shown to increase bubble size, and these factors limit the usefulness of one previously tested stage decompression procedure for the Shuttle. The method might be helpful for evaluating decompression procedures before testing.

decompression  
 decompression sickness  
 decompression theory  
 decompression limits  
 altitude bends  
 bubbles  
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The atmospheres used in the U. S. space program have been 100% oxygen at a pressure of about 5 psia in Gemini, Apollo, and Skylab (3) and air at sealevel pressure in the Shuttle. On the Apollo-Soyuz mission, the Russian atmosphere was 31% oxygen and 69% nitrogen at a pressure of 10 psia (6). Spacesuit atmospheres have been 100% oxygen at pressures of between 3.5 and 4.3 psia (1,3).

Many conflicting factors enter into the selection of these atmospheres. A pure oxygen atmosphere at low pressure allows considerable savings in vehicle weight and permits immediate transition of a flight crew to suit pressure for extravehicular activity (EVA) without the risk of decompression sickness (4). At low pressures, however, voice communications are difficult, and heat transfer efficiency is reduced which interferes with the cooling of electrical equipment. With pure oxygen, the fire hazard is increased, and there is a risk of aural and pulmonary atelectasis (17). These problems are avoided in the air atmosphere of the Shuttle, but a long decompression procedure is necessary before the crew can safely perform EVA at the present suit pressure of 4.3 psia (22). A higher pressure suit might eliminate the decompression requirement, but suit flexibility would be sacrificed.

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This paper describes a theoretical method for predicting those atmospheres which avoid the risk of decompression sickness. With this knowledge, the other factors affecting atmosphere selection can be evaluated independently. The method has evolved from the work of Nims (15), Hills (13), Hennessy and Hempleman (10), and Vann (21).

The method is most applicable to long duration missions such as might occur in a space station. In this situation, there would be adequate time after decompression from sealevel for nitrogen in the lungs and tissues to equilibrate before further decompression to suit pressure. The problem of nitrogen elimination by oxygen breathing at sealevel is addressed indirectly in an analysis of stage decompression procedures for the Shuttle.

#### THE CAUSE OF DECOMPRESSION SICKNESS

Animal experiments and autopsies of divers and caisson workers led Hill (12) to conclude that decompression sickness was caused by undissolved gas in the blood and tissues. The variety and severity of the symptoms depended upon the volume and location of the gas. Unconsciousness and death were often found to result from gas bubbles in the brain, dyspnea and chokes from gas in the pulmonary arteries, and paralysis from gas in the spinal cord. The etiology of the minor forms of decompression sickness was less clear because smaller volumes of gas were involved, but it seemed probable that muscle and joint pain were the result of bubbles in ligaments, fascia, periosteum, muscle spindles, and nerve sheaths.

Undissolved gas is still widely accepted as the initiating cause of decompression sickness, but the responses of the body to this gas are now recognized to be biochemical as well as mechanical. The details of the mechanisms by which gas bubbles cause decompression symptoms are not completely understood and will not be directly addressed here. Instead, it is assumed only that the risk of symptoms is high when a large volume of undissolved gas is present and, conversely, that the risk is low when little gas is present. Furthermore, as proposed by Hempleman (9), it is postulated that major symptoms will be rare if minor symptoms can be avoided consistently. With these assumptions, the problem becomes to find the smallest gas volume which results in decompression sickness and to relate this volume to the smallest pressure reductions known to cause symptoms in man.

#### THE CRITICAL BUBBLE VOLUME HYPOTHESIS

Figure 1 shows a tissue which is decompressed from a barometric pressure  $P_{B1}$  to a pressure  $P_{B2}$  where a bubble of critical volume forms. The critical bubble volume is defined as the largest volume which can be present without causing decompression sickness. If the critical bubble volume is designated as  $V_c$ , then a pressure reduction to less than  $P_{B2}$  causes the bubble to become larger than  $V_c$ , and the risk of decompression sickness exists.

A relationship between bubble volume and pressure reduction can be found in the following manner. It is assumed that diffusion within the tissue is instantaneous and that the pressure change is very

rapid. Thus, no nitrogen is lost during decompression, and the quantity of nitrogen dissolved in the tissue at PB1 is equal to the sum of the dissolved nitrogen at PB2 plus the nitrogen in the bubble. This is an expression of the law of conservation of mass.

The molar quantity of nitrogen dissolved at PB1 is

$$ND1 = S*Vt*(PtN2)1$$

where S is the nitrogen solubility in tissue in moles/ml tissue/psi, Vt is the tissue volume in ml, and (PtN2)1 is the tissue nitrogen tension in psi. Similarly, the molar quantity of dissolved nitrogen at PB2 is

$$ND2 = S*Vt*(PtN2)2$$

where (PtN2)2 is the nitrogen tissue tension at PB2 in psi. Although the tissue may have both fat and lean components, its nitrogen solubility is represented by a single quantity, S, as diffusion has been assumed to be instantaneous.

The molar quantity of nitrogen in the bubble at PB2 is defined by the ideal gas law as

$$NB2 = \frac{(PtN2)2*Vc}{RT}$$

where R and T are the general gas constant and the absolute temperature in appropriate units. The nitrogen partial pressure in the bubble and the tissue nitrogen tension are equal because of instantaneous diffusion.

By the law of conservation of mass, the dissolved nitrogen (ND1) at PB1 is equal to to the sum of the dissolved nitrogen (ND2) at PB2



and nitrogen in the bubble (NB3) at PB2 or

$$ND1 = ND2 + NB2$$

Substituting for these terms and solving for (PtN2)1 gives

$$(PtN2)1 = (Ac + 1)*(PtN2)2 \quad (1)$$

where

$$Ac = \frac{Vc}{S*Vt*R*T}$$

Ac is the ratio of the moles of nitrogen in the bubble to the moles of nitrogen dissolved in tissue.

At PB1, Dalton's law of partial pressures requires that the sum of the alveolar partial pressures of nitrogen, oxygen, and carbon dioxide (PAN2, PAO2, and PACO2) and the water vapor pressure (PH2O) be equal to PB1 or

$$PB1 = PAN2 + PAO2 + PACO2 + PH2O$$

If the alveolar partial pressures of all gases are equal to their corresponding arterial tensions (PaN2, PaO2, and PaCO2), then from above

$$PB1 = PaN2 + PaO2 + PaCO2 + PH2O$$

Since the tissues are assumed to be in equilibrium with nitrogen at PB1, the tissue nitrogen tension is equal to the arterial tension, and it can be found that

$$(PtN2)1 = PB1 - PaO2 - PaCO2 - PH2O \quad (2)$$

Rahn and Fenn (16) give the alveolar oxygen partial pressure as

$$PAO2 = PIO2 - PaCO2/RQ + FIO2*(PaCO2/RQ - PaCO2)$$

where PIO2, RQ, and FIO2 are the inspired oxygen partial pressure,

the respiratory quotient, and the inspired oxygen fraction. Setting

$$PAO_2 = PaO_2$$

and

$$PIO_2 = FIO_2 * PB_1$$

and letting

$$RQ = 1$$

which introduces little error, it is found that

$$PaO_2 = FIO_2 * PB_1 - PaCO_2$$

Substituting this for  $PaO_2$  in (2), gives

$$(P_{tN_2})_1 = (1 - FIO_2) * PB_1 - PH_2O \quad (3)$$

In the bubble at  $PB_2$ , Dalton's law requires that

$$PB_2 + P_e = (P_{tN_2})_2 + P_{tO_2} + P_{tCO_2} + PH_2O$$

where  $P_e$  is a pressure component due to surface tension and tissue elasticity and  $P_{tO_2}$  and  $P_{tCO_2}$  are the oxygen and carbon dioxide tensions in tissue. Solving for  $(P_{tN_2})_2$ ,

$$(P_{tN_2})_2 = PB_2 + P_e - P_{tO_2} - P_{tCO_2} - PH_2O \quad (4)$$

Substituting (3) and (4) for  $(P_{tN_2})_1$  and  $(P_{tN_2})_2$  in (1) and solving for  $PB_2$ ,

$$PB_2 = \frac{(1 - FIO_2) * PB_1 - PH_2O}{Ac + 1} - P_e + P_{tO_2} + P_{tCO_2} + PH_2O \quad (5)$$

#### MARGINAL DECOMPRESSION EXPOSURES

Equation (5) predicts the pressure  $PB_2$  to which decompression is marginally safe after an exposure at a pressure  $PB_1$  of sufficient length to ensure equilibrium between nitrogen in the lungs and in the tissues. If venous values are assigned to  $P_{tO_2}$  and  $P_{tCO_2}$ , then

$P_{tO_2}$  = 40 mmHg for tissue oxygen tension,  
 $P_{tCO_2}$  = 45 mmHg for tissue carbon dioxide tension,  
 $P_{H_2O}$  = 46 mmHg for water vapor pressure, and  
 $F_{IO_2}$  = 0.21 for the oxygen fraction at PB1 if air is used.

The remaining unknowns,  $A_c$  and  $P_e$ , can be found if two pairs of marginal decompression exposures are known.

For the first marginal exposure, PB1 is sealevel pressure (14.7 psia), and PB2 is the lowest altitude at which decompression sickness occurs. Fryer (7) reports this altitude to be 18,500 ft. To be conservative, PB2 will be taken as a lower altitude of 18,000 ft (PB2 = 7.35 psia). For the second exposure, PB1 is the shallowest depth which results in decompression sickness when an air-equilibrated diver ascends directly to the surface (PB2 = 14.7 psia). Behnke and Jones (2) and Spencer (19) report this depth to be 25 feet of seawater (FSW). To be conservative, PB1 will be taken as 24 FSW (25.84 psia).

Substitution of the values

$$(PB_1, PB_2) = (14.7 \text{ psia}, 7.35 \text{ psia})$$

and

$$(PB_1, PB_2) = (25.84 \text{ psia}, 14.7 \text{ psia})$$

into equation (5) results in two equations with unknowns  $A_c$  and  $P_e$  which can be solved simultaneously to give

$$A_c = 0.1938$$

and

$$P_e = 4.1851 \text{ psi}$$

Since  $A_c$  is the ratio of nitrogen in the bubble to nitrogen dissolved in tissue, it can be found that about 16% of the total nitrogen is in

the bubble while 84% is dissolved. As the values for  $A_c$  and  $P_e$  were derived from the smallest pressure reductions reported to cause marginal decompression illness, it is expected that decompression procedures based upon them will be safe for a greater fraction of the population.

If  $P_e$  is assumed to be constant at all bubble volumes, then equation (5) holds for any bubble volume,  $V$ , where the parameter  $A_c$  is replaced by the parameter  $A$  defined as

$$A = \frac{V}{S \cdot V_t \cdot R \cdot T}$$

Dividing  $A$  by  $A_c$ , it can be shown that

$$A = A_c \cdot \frac{V}{V_c}$$

where a risk of decompression sickness exists if  $V/V_c$  exceeds 1.0. With this definition for  $A$ , equation (5) becomes

$$P_{B2} = \frac{(1 - F_{IO_2}) \cdot P_{B1} - P_{H_2O}}{A_c \cdot V/V_c + 1} - P_e + P_{tO_2} + P_{tCO_2} + P_{H_2O} \quad (6)$$

#### SPACE STATION ATMOSPHERES AND SUIT PRESSURES

Equation (6) may be used to find the final pressure  $P_{B2}$  which results in a bubble of fractional volume  $V/V_c$  after decompression from an initial pressure  $P_{B1}$  and oxygen fraction  $F_{IO_2}$ . Figure 2 illustrates how this equation might be applied to the transfer of a flight crew from sealevel to a space station where they would remain for an extended period performing regular EVA.

A Shuttle having an air atmosphere at 1 ATA transports the crew from Earth to an orbiting space station. Upon arrival at the station, the crew passes through an airlock into the station which has a pressure (PB)station and an oxygen fraction (FIO2)station. After sufficient time to permit nitrogen in their tissues to equilibrate with nitrogen in the station atmosphere, the crew decompresses to a pressure (PB)suit in 100% oxygen for EVA. Decompression to both (PB)station and (PB)suit results in the formation of a bubble of fractional volume  $V/V_c$ . (A similar procedure is used if the bubbles are of unequal volume.)

To find the station pressure, the desired bubble volume  $V/V_c$  is substituted into equation (6) where FIO2 is 0.21 and PB1 is 1 ATA. The suit pressure is determined in the same manner after substituting the calculated value of (PB)station for PB1 and the appropriate values for  $V/V_c$  and (FIO2)station. This procedure was used to develop Table 1 for  $V/V_c$  values of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 and for (FIO2)station values of from 0.27 to 0.34. For example, if bubbles having a fractional volume of 0.4 are permitted to form and if the station FIO2 is 0.30, (PB)station is 8.3 psia and the lowest allowable (PB)suit is 2.91 psia. The oxygen partial pressures in the station and suit under these conditions are 0.17 and 0.20 ATM.

The atmospheres in Table 1 are subject to restrictions imposed by hypoxia, suit flexibility, fire hazard, and decompression risk. Resting men can tolerate oxygen partial pressures as low as 0.11 ATM with little difficulty, but their capacity for exercise is severely

limited (14). In experiments where men exercised on a bicycle ergometer while breathing air at simulated altitudes, decreased exercise tolerance was observed at 10,000 feet but not at 5,000 feet (20). The oxygen partial pressure in air at 5,000 feet is about 0.17 ATM (2.5 psi), and this value has been applied to Table 1 as the lower limit for hypoxic exposure.

Another limitation to exercise capacity is the stiffness of the suits which flight crews wear during EVA. These suits are most flexible at low pressures. Since the gas in them is 100% oxygen, the lowest possible suit pressure is set by the hypoxic limit of 0.17 ATM (2.5 psi). Suit pressures above the current level of 4.3 psia could be used if a more flexible design were available.

If the station  $PIO_2$  is not to be less than the hypoxic limit when the station pressure is below 12 psia, the  $FIO_2$  must be raised above 0.21. Associated with this rise is an increase in fire hazard which can be measured as a percentage decrease in combustion time relative to the combustion time in air at 14.7 psia. Estimates of decreased combustion times for elevated  $FIO_2$ 's were derived from data of Simons and Archibald (18). These estimates are listed in Table 1 and show that as the  $FIO_2$  rises from 0.21 to 0.34, the combustion time decreases by approximately 24%.

Table 1 can be thought of as a risk-benefit matrix in which the station atmosphere is determined by the station  $FIO_2$ , and this is chosen in a compromise between suit flexibility, fire safety, and decompression risk. The risk of hypoxia increases diagonally from the

bottom left corner to the top right corner. Lower suit pressures and greater suit flexibility are achieved by moving in the same direction. Fire hazard increases from top to bottom as the station FIO<sub>2</sub> rises. The risk of decompression sickness increases when moving from left to right as the fractional bubble volume increases from 0.0 to 1.0. Atmospheres having the larger bubble volumes should be avoided since exercise after decompression causes an increased risk of decompression sickness (8).

#### STAGE DECOMPRESSION PROCEDURES FOR THE SHUTTLE

The effect of exercise after decompression can be quite significant. Gray found that the incidence of decompression sickness at pressures of 3.8 to 3.0 psia was increased 15 to 32% in subjects who did 5 push-ups and 5 deep knee bends every 15 minutes (5). The increased incidence was approximately equivalent to an extra 5,000 feet of decompression.

Henry observed that the rise in decompression sickness was related to the severity of the exercise, and he concluded that locally elevated CO<sub>2</sub> production was causing bubbles to expand (11). Burkhardt, on the other hand, found that the incidence was reduced by hyperventilation which Nims concluded was an indication of a decrease in bubble volume as a result of CO<sub>2</sub> elimination (15).

These explanations suggest that exercise might be simulated by a virtual decompression which causes existing bubbles to expand. This tactic can be used to analyze the effects that exercise may have had

during tests of stage decompression procedures for the Shuttle.

Adams et al. (1) exposed 18 subjects to 9.2 psia on 28% oxygen for 12 hours and then on 100% oxygen for 45 minutes before ascent to a pressure of 4.0 psia. After decompression, the subjects exercised for 1 out of every 8 minutes. This procedure resulted in one case of decompression sickness. In another test, Waligora et al. (22) exposed 50 subjects to 10.2 psia on 26% oxygen for 12 to 18 hours and then on 100% oxygen for 40 to 90 minutes before ascent to 4.3 psia. Upon arrival at 4.3 psia, the subjects exercised for 8 out of every 16 minutes. This procedure resulted in 15 cases of decompression sickness.

It is uncertain whether these procedures produced complete equilibrium between nitrogen in the lungs and tissues. In the event that equilibrium was not complete,  $(P_{tN_2})_1$  is given by

$$(P_{tN_2})_1 = F_{eq} * ((1 - F_{IO_2}) * P_{B1} - 0.79) + 0.79 - P_{H_2O} \quad (7)$$

where  $F_{eq}$  is the nitrogen equilibrium fraction. Before any equilibration has occurred,  $F_{eq}$  is zero and

$$(P_{tN_2})_1 = 0.79 - P_{H_2O}$$

After equilibrium is complete,  $F_{eq}$  is one and  $(P_{tN_2})_1$  is given by equation (3).

With the aid of equation (7), it may be found that

$$\frac{V}{V_c} = \left( \frac{F_{eq} * ((1 - F_{IO_2}) * P_{B1} - 0.79) + 0.79 - P_{H_2O}}{P_{B2} + P_e - P_{tO_2} - P_{tCO_2} - P_{H_2O}} - 1 \right) / A_c \quad (8)$$

Equation (8) was used to generate Figs. 3 and 4 which show the effects of exercise and incomplete nitrogen equilibrium on the 9.2



and 10.2 psia Shuttle decompression procedures. Exercise is simulated by a virtual decompression of 5,000 ft as suggested by Gray's observations (5). This is probably too great for the 9.2 psia procedure but may be reasonable for the 10.2 psia procedure.

The 9.2 psia procedure had a 6% incidence of decompression sickness. In Fig. 3, this procedure is seen to be safe ( $V/V_c < 1.0$ ) for resting subjects when nitrogen equilibrium is more than 80% complete. For exercising subjects, however, it is safe only at complete equilibrium. Nitrogen equilibrium is estimated to have been 80 to 90% complete.

The 10.2 psia procedure had a decompression sickness incidence of 30%. In Fig. 4, this procedure is seen to be safe for resting subjects when nitrogen equilibrium is more than 90% complete. The procedure appears to be unsafe, however, for anymore than minimal exercise.

This discussion has illustrated a retrospective use of equation (8). A similar analysis applied in advance might aid the selection of space craft atmospheres and the development of stage decompression procedures for the future.

## ACKNOWLEDGMENTS

This work was supported under Office of Naval Research Contract N00014-83-K-0019. The authors wish to thank David J. Horrigan, Jr. for his excellent suggestions and review of the manuscript.

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Table 1. Station and suit atmospheres. (PI02 is in ATM and PB is in psia.)

(FI02) station	V/Vc	0.0	0.2	0.4	0.6	0.8	1.0	% Decrease in Combustion Time
	(PB)station	9.07	8.67	8.30	7.95	7.63	7.33	
0.27	(PI02)station	0.17	a	a	a	a	a	14
	(PB)suit	4.08						
	(PI02)suit	0.28						
0.28	(PI02)station	0.17	a	a	a	a	a	15
	(PB)suit	3.99						
	(PI02)suit	0.27						
0.29	(PI02)station	0.18	0.17	a	a	a	a	17
	(PB)suit	3.90	3.42					
	(PI02)suit	0.27	0.23					
0.30	(PI02)station	0.19	0.18	0.17	a	a	a	19
	(PB)suit	3.81	3.34	2.91				
	(PI02)suit	0.26	0.23	0.20				
0.31	(PI02)station	0.19	0.18	0.18	0.17	a	a	21
	(PB)suit	3.72	3.25	2.84	2.47			
	(PI02)suit	0.25	0.22	0.19	0.17			
0.32	(PI02)station	0.20	0.19	0.18	0.17	0.17	a	22
	(PB)suit	3.63	3.17	2.76	2.40	2.50		
	(PI02)suit	0.25	0.22	0.19	0.16	0.17b		
0.33	(PI02)station	0.20	0.19	0.19	0.18	0.17	a	23
	(PB)suit	3.54	3.08	2.68	2.50	2.50		
	(PI02)suit	0.24	0.21	0.18	0.17b	0.17b		
0.34	(PI02)station	0.21	0.20	0.19	0.18	0.18	0.17	24
	(PB)suit	3.45	3.00	2.61	2.50	2.50	2.50	
	(PI02)suit	0.23	0.20	0.18	0.17b	0.17b	0.17b	

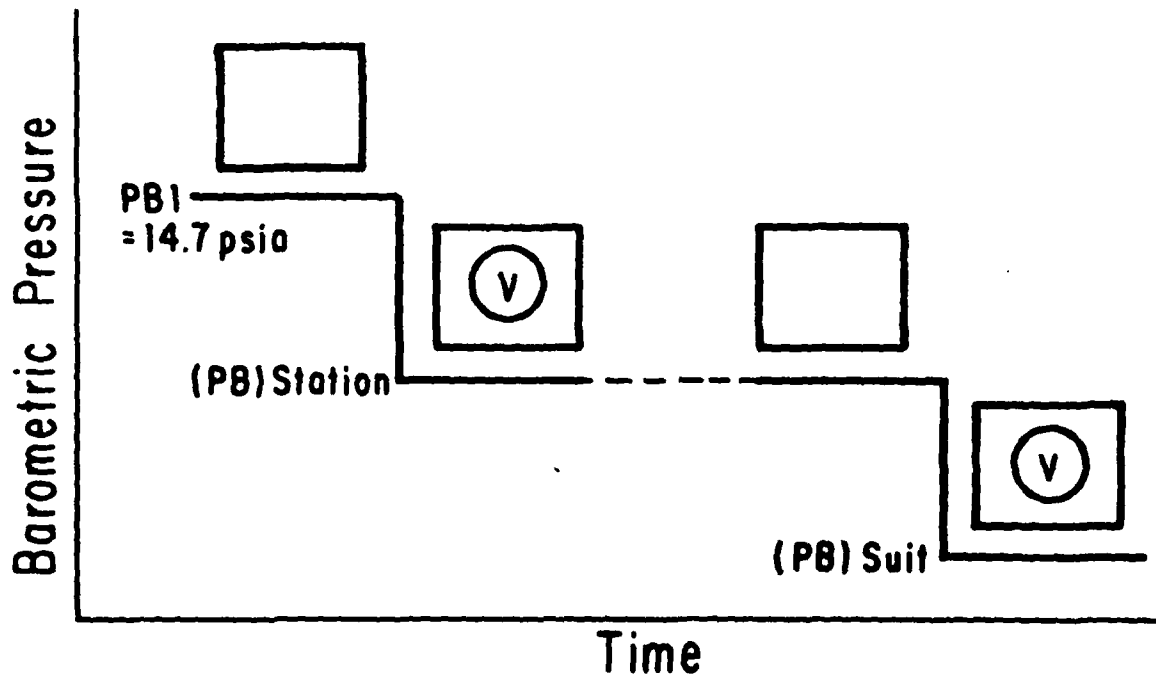
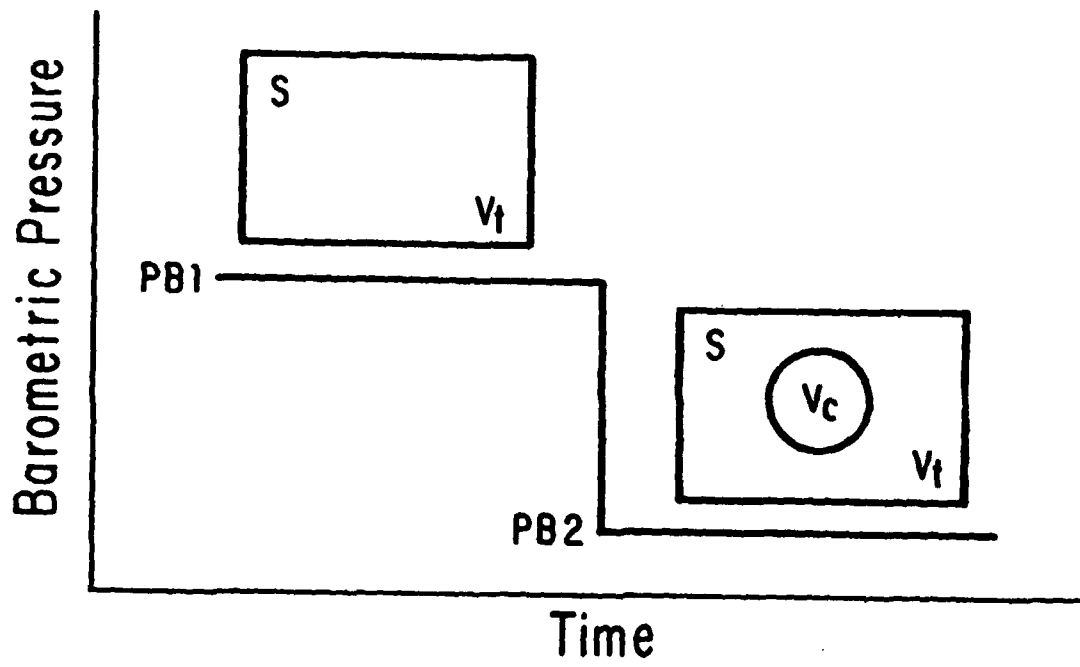
a - (PI02)station &lt; 0.17 ATM

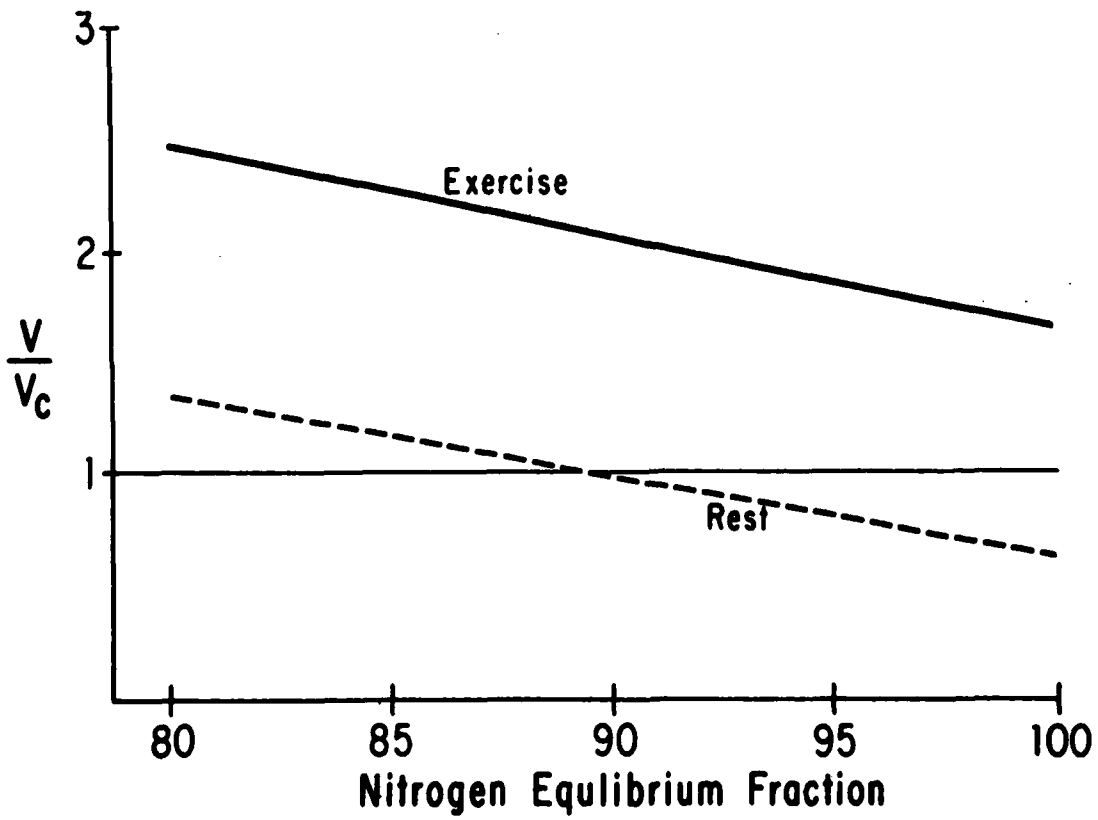
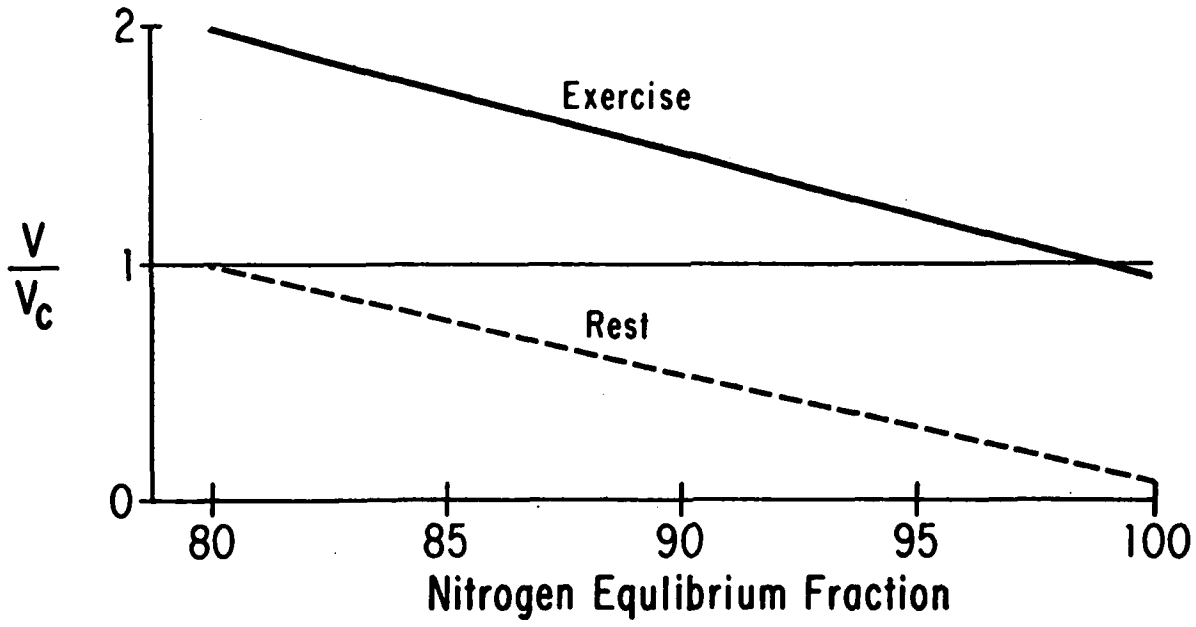
b - (PI02)suit raised to 0.17 ATM

## FIGURE CAPTIONS

1. Formation of a bubble of critical volume.
2. Decompression from sealevel to station and suit pressures.
3. Shuttle decompression procedure with  $PB1 = 9.2$  psia,  $FI02 = 0.28$ , and  $PB2 = 4.0$  psia. Decompression sickness incidence was 6%.
4. Shuttle decompression procedure with  $PB1 = 10.2$  psia,  $FI02 = 0.26$ , and  $PB2 = 4.3$  psia. Decompression sickness incidence was 30%.







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**SELECTION OF SPACE CRAFT AND SPACE SUIT ATMOSPHERES. R.D. Vann and J.R. Torre-Bueno\***. F.G. Hall Laboratory and Department of Anesthesiology, Box 3823, Duke University Medical Center, Durham, NC 27710.

A theoretical method for selecting space craft and space suit atmospheres has been developed. The method assumes that gas bubbles cause decompression sickness (DCS) and that the risk increases when a critical bubble volume is exceeded. The method is consistent with empirical observations of hypo- and hyperbaric decompression exposures for humans. Space station atmospheres are determined so that flight crews may decompress immediately from sealevel to station pressure without preoxygenation. Bubbles form as a result of this decompression but are less than the critical volume. The bubbles are absorbed during an equilibration period after which immediate transition to suit pressure is possible. For example, with a station pressure of 9.1 psia and 31% O<sub>2</sub>, a suit pressure of 3.7 psia may be used. Previously tested stage decompression procedures for the Shuttle (9.2 psia with 27% O<sub>2</sub> to 4.0 psia resulted in 1 DCS/18 exposures; 10.2 psia with 26% O<sub>2</sub> resulted in 15 DCS/50 exposures) were evaluated. The 9.2 psia procedure was predicted to be the safer. Exercise after decompression and incomplete nitrogen equilibrium were shown to increase bubble size, and these factors limited the usefulness of the 10.2 psia procedure. Thus, the method allows an assessment of decompression procedures prior to actual testing.

This work was supported by Office of Naval Research Contract N00014-83-K-0091.

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