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# The Mars Project: Avoiding Decompression Sickness on a Distant Planet

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May 2000

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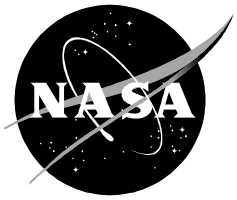

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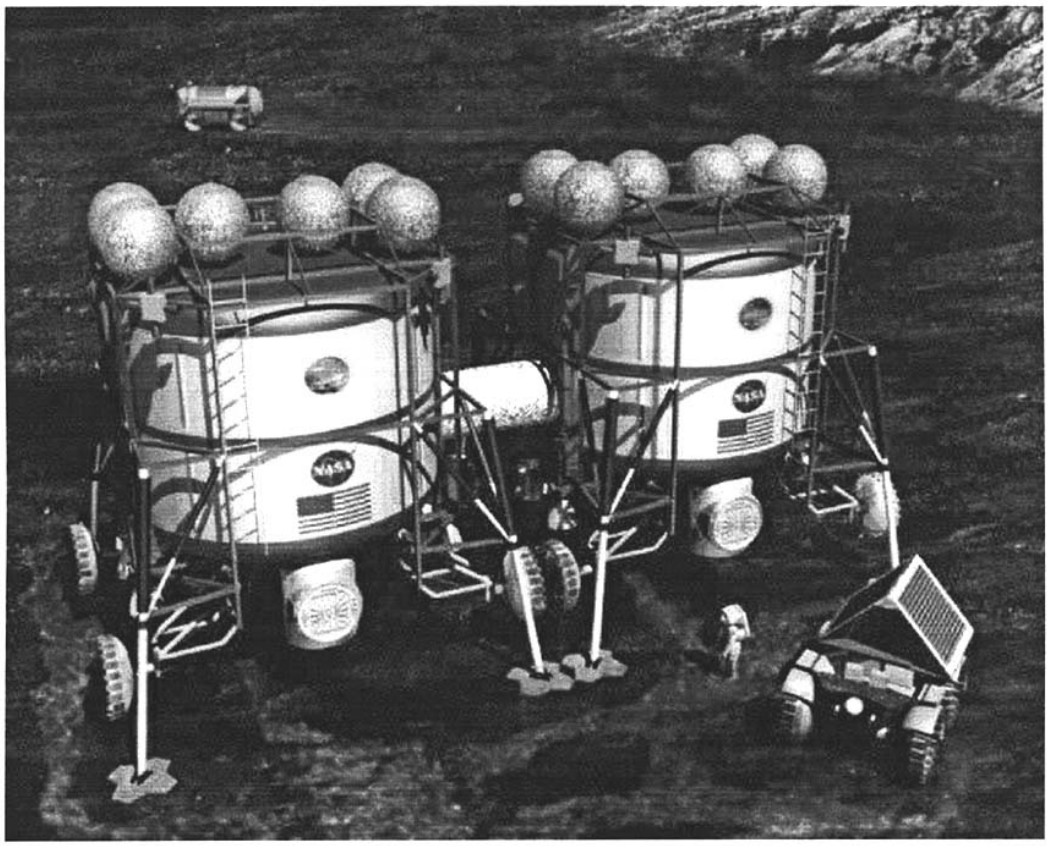
## Acronyms and Nomenclature

| | |
|---|---|
| Ar | argon |
| BGI | bubble growth index |
| $CF_4$ | carbon tetrafluoride |
| $CO_2$ | carbon dioxide |
| DCS | decompression sickness |
| EVA | extravehicular activity |
| fsw | feet sea water |
| He | helium |
| kPa | kilopascals |
| $N_2$ | nitrogen |
| $N_2O$ | nitrous oxide |
| $O_2$ | oxygen |
| psia | pounds per square inch |
| $SF_6$ | sulfur hexafluoride |
| tigp | total inert gas pressure |
| TR | tissue ratio |

## Abstract

A cost-effective approach for Mars exploration is to use the available resources, such as water and atmospheric gases. Nitrogen ($N_2$) and argon (Ar) in a concentration ratio of 1.68/1.0 are available and could form the inert gas component of a habitat atmosphere at 8.0, 9.0, or 10.0 pounds per square inch (psia). The habitat and space suit are designed as an integrated system: a comfortable living environment about 85% of the time and a safe working environment about 15% of the time. A goal is to provide a system that permits unrestricted exploration of Mars. However the risk of decompression sickness (DCS) during the extravehicular activity in a 3.75-psia suit, after exposure to any of the three habitat conditions may limit unrestricted exploration. This communication is an evaluation of the risk of DCS since a significant proportion, about 25%, of a trinary breathing gas in the habitat might contain Ar. I draw on past experience and published information to extrapolate into untested, multivariable conditions to evaluate risk. A rigorous assessment of risk as a probability of DCS for each habitat condition is not yet possible. Based on many assumptions about Ar in hypobaric decompressions, I conclude that the presence of Ar significantly increases the risk of DCS. Constrained as I am by this cost-effective approach, the risk is significant even with the best habitat option: 2.56 psia oxygen ($O_2$, 32%), 3.41 psia $N_2$ (42.6%), and 2.20 psia Ar (25.2%). Several hours of prebreathing 100% $O_2$, a higher suit pressure, or a combination of other important variables such as limited exposure time on the surface or exercise during prebreathe would be necessary to reduce the risk of DCS to an acceptable level. The acceptable level for DCS risk on Mars has not yet been determined. Mars is a great distance from Earth and therefore from primary medical care. The acceptable risk would necessarily be defined by the capability to treat DCS in the Rover vehicle, in the habitat, or both.



***An early artist's conception of a mobile Mars habitat.***

Courtesy of the Mars Society Web Page: www.marssociety.org,
October 1999.

## Introduction

Men and women are alive today, although perhaps still in diapers, who will explore the surface of Mars. Two achievable goals to enable this exploration are to use Martian resources, and to provide a safe means for unrestricted access to the surface. This communication is my assessment of the risk of decompression sickness (DCS) while using existing low-pressure suit technology in conjunction with an atmosphere in the habitat that may contain argon (Ar). The habitat and space suit must be designed as an integrated, complementary, system: a comfortable living environment about 85% of the time and a safe working environment about 15% of the time. Once the appropriate habitat pressure and breathing gas composition are defined, oxygen ($O_2$) prebreathe procedures to avoid DCS before surface exploration can be developed.

The choice of a breathing atmosphere for the Mars habitat is a problem with multiple variables driven by engineering, medical, and operational requirements. The engineering drivers are to use the lowest possible habitat pressure, which conserve limited resources, use inert gases in the Martian atmosphere without costly processing, and use a 3.75 pounds per square inch (psia) soft suit with 100% $O_2$. The medical drivers are to provide adequate alveolar $O_2$ pressure in the habitat and suit, to not increase the risk of fire, and to incur no DCS that cannot be treated effectively on Mars. An operational driver is to provide for unlimited access to the surface without time-consuming prebreathing. There are many other factors not considered here about living in a low-pressure habitat with an exotic breathing mixture: a significant increase in electrical power for cooling fans, valid issues about food preparation (1), problems with voice communication and noise issues (25), leakage problems, and possibly even an alteration in metabolism (15,16). The engineering, operations, and medical community will evaluate and "trade" various options until a safe system is devised.

## Martian Resources

My assumption is that an automated system sent to Mars before a crewed flight will extract and store the thin Martian atmosphere that exerts a total pressure less than 5 mmHg. This pressure is equivalent to the pressure at about 110,000 ft above the Earth. The atmosphere is composed of 95.7% carbon dioxide ($CO_2$), to be used to make $O_2$, 2.7% nitrogen ($N_2$), and 1.6% Ar (21), a ratio of 1.68 $N_2$ to 1.0 Ar. From an engineering standpoint, the preference would be to not separate the inert gases into different containers; this takes too much energy and

technology (26). Therefore the atmosphere for the habitat would have $N_2$ and Ar at the ratio already in the atmosphere with the balance of $O_2$ to achieve an acceptable total pressure (26).

## Minimum Oxygen Pressure

The first requirement of an atmosphere in a habitat or space suit is to provide an adequate $O_2$ partial pressure in the breathing mixture to prevent hypoxia. Equation 1 is the alveolar $O_2$ equation, which is used to compute alveolar $O_2$ pressure as a function of environmental and physiological variables,

$$P_AO_2 = F_iO_2 * (P_B - 47) - [P_ACO_2 * (F_iO_2 + (1 - F_iO_2) / RQ)], \quad (1)$$

where $P_AO_2$ is alveolar partial pressure of oxygen (mmHg), $F_iO_2$ is oxygen decimal fraction in the breathing atmosphere (0.21 at sea level), $P_B$ is barometric pressure of the breathing mixture (mmHg), $P_ACO_2$ is the alveolar partial pressure of $CO_2$ (mmHg), and RQ is the unitless respiratory exchange ratio, about 0.85 under most conditions. Equation 1 helps to define a hypoxic environment. Hypoxia is a generic term that describes $O_2$ deficiency in the tissues due to various causes: reduced partial pressure in the breathing mixture, inability of $O_2$ to be transported by the blood, or inability of the tissue to use an adequate $O_2$ supply provided by the cardiorespiratory system (9). My specific concern is hypoxia caused by an inadequate partial pressure of $O_2$ in the breathing mixture. In our case, the $O_2$ fraction in the habitat is set as high as possible without increasing flammability while the total habitat pressure is set as low as possible without producing chronic hypoxia, and reducing the inert gas tension in the tissues as much as possible. The combination of highest $O_2$ fraction in the habitat and the lowest habitat pressure must provide for adequate $P_AO_2$.

Figure 1 is the $O_2$ dissociation curve in two forms: 1A shows the saturation of hemoglobin as a function of alveolar $O_2$ pressure and 1B shows the amount (ml) of $O_2$ carried on the hemoglobin in 100 ml blood (vol.%), also a function of alveolar $O_2$ pressure. The curve for 1B applies to “normal” blood at 45% hematocrit with 15 grams of hemoglobin per 100 ml of blood, with each gram of hemoglobin able to carry 1.39 ml of $O_2$. The hemoglobin is 95% saturated with $O_2$ at a $P_AO_2$ of about 80 mmHg. This condition is equivalent to living at 5000 feet altitude, and is considered about the lowest “normal” alveolar $O_2$ pressure in this discussion.

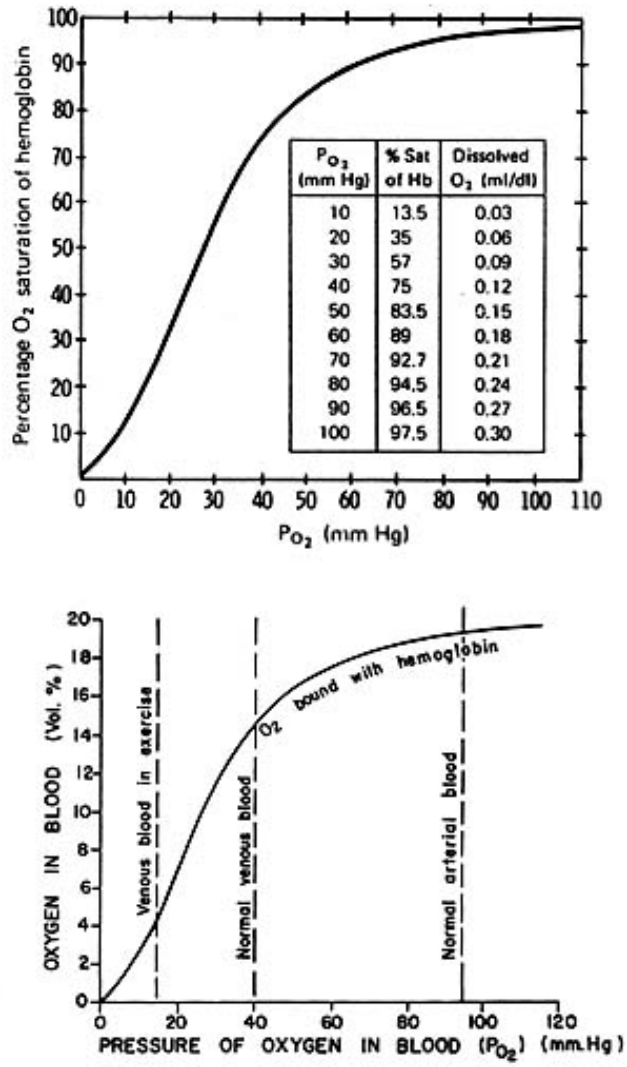



***Figure 1. The normal $O_2$ dissociation curve (1A), and extraction of $O_2$ from the blood under normal and exercise conditions (1B). The $O_2$ dissociation curve helps to define the minimum $O_2$ partial pressure needed in a breathing atmosphere.***

## Maximum Oxygen Concentration

The single most critical constraint that prevents quick access to the Martian surface without serious risk of DCS is the limit placed on the $O_2$ concentration in the habitat. Many fires and needless deaths in chambers are due to increased flammability caused by high $O_2$ content

and poor selection of materials (10,32). Equation 2 defines the limit of $O_2$ concentration as a function of total pressure (10).

$$\text{allowable } O_2\% = 23.45 / (P2 / 14.7)^{0.5}, \quad (2)$$

where allowable $O_2$% is the concentration that does not increase burning rate of select materials above that achieved in air at 1 **ATA**, and P2 is barometric pressure of the breathing mixture (psia). The allowable $O_2$% at 8.0, 9.0, and 10.0 psia are 32%, 30%, and 28%, respectively. Another source (32) sets the allowable $O_2$% to about 38% at 7.34 psia while Eq. 2 would compute 33% as acceptable. Selecting the correct $O_2$ concentration for a hypobaric Mars habitat is critical in defining the subsequent decompression procedure. In defining the upper limit for $O_2$ concentration, it must not be overlooked that flame propagation is also a function of gravity. A flame in still air in zero gravity is self-limiting (extinguished) because the combustion products are not conveyed away since the density gradient that induces air movement in a gravity field is not effective in zero gravity. The reduction of natural convection in a Mars habitat at $3/8^{th}$ gravity may permit $O_2$ concentrations at any habitat pressure to be increased. There are also issues of initial ignition energy and flame propagation when the atmosphere contains appreciable Ar. If a flammability constraint does not allow for the safe and routine access to the surface, and other options to change the concentrations of Ar and $N_2$ are not cost-effective for the entire habitat, then consideration must be given to provide a special prebreathe room.

## The Mars Habitat

Various options using $N_2$ and $O_2$ that were previously evaluated in 1991 (1) were not constrained to use Martian resources. The elimination of prebreathe time was a major consideration. Some of those recommendations were: a 10.0 psia habitat at 30% $O_2$ with a 5.85-psia $O_2$ suit, a 14.7-psia habitat at 21% $O_2$ with a 9.5-psia $O_2$ suit (an option that provided an Earth-like condition in which to do experiments), and a combination of the above by partitioning the habitat into two pressure zones. Notice that suit pressure was a variable, which allowed several options. In this evaluation, a suit pressure of 3.75 psia is considered “fixed,” i.e., the decision to use 3.75 psia has already been made.

Ar in the breathing mixture presents a special challenge when trying to avoid DCS due to its higher solubility (about twice) compared to $N_2$. Ar has about the same solubility as $O_2$. Argon comes in three forms: Ar-36, Ar-38, and Ar-40. The first two are from the decay of

radioactive potassium in the Earth's crust, and are barely present on Mars (21). I need only to consider Ar-40, which contributes about 0.93% of the atmosphere on Earth.

Table I lists the three options evaluated for a Martian habitat atmosphere.

***Table I. Three Options Evaluated for a Martian Habitat Atmosphere***

| Option | Total Pressure | (Partial Pressure as psia and % of Total Pressure) $O_2$ | $N_2$ | Ar |
|---|---|---|---|---|
| 1 | 8.0 psia | 2.56 (32.0%) | 3.41 (42.6%) | 2.02 (25.2%) |
| tissue pressure* | | | 3.03 | 1.80 |
| 2 | 9.0 psia | 2.70 (30.0%) | 3.95 (43.9%) | 2.34 (26.0%) |
| tissue pressure* | | | 3.58 | 2.11 |
| 3 | 10.0 psia | 2.80 (28.0%) | 4.52 (45.2%) | 2.68 (26.8%) |
| tissue pressure* | | | 4.14 | 2.45 |

* tissue pressures for $N_2$ and Ar are critical variables, and are estimated in Table II for Option 1, as an example.

In each case, the person is in equilibrium, or "saturated," with the breathing environment before the decompression to 3.75 psia. For each ambient pressure, the proper $N_2$–Ar concentration ratio was calculated using Eq. 3. Equation 3 computes the $N_2$ pressure component of the total inert gas pressure (tigp) in a particular habitat condition to achieve a 1.68 $N_2$/1.0 Ar pressure ratio.

$$N_2 \text{ pressure} = (\text{tigp} * 1.68)/2.68. \quad (3)$$

It is not a trivial task to compute the $N_2$ and Ar pressures for various habitat pressures to give the 1.68 $N_2$/1.0 Ar ratio available on Mars, so the derivation of the equation is documented in Appendix A. For example, the 10-psia habitat pressure has 28% $O_2$, or 2.8 psia $O_2$. This leaves the tigp = 10 - 2.8 = 7.2 psia. The $N_2$ pressure from Eq. 3 is (7.2 * 1.68)/2.68 = 4.51 psia, and the Ar pressure is the difference between 7.20 - 4.51 = 2.68. The concentrations of $O_2$, Ar, and $N_2$ are 28.0%, 26.8%, and 45.1% respectively. The ratio of $N_2$ to Ar concentration or pressure in this example is 1.68.

Table II shows the partial pressures of the metabolic as well as the inert gases in the lung and tissues for Option 1. This level of detail is necessary in order to compute a simple mass balance later in this report of the inert gases in the tissues as well as provide initial conditions for

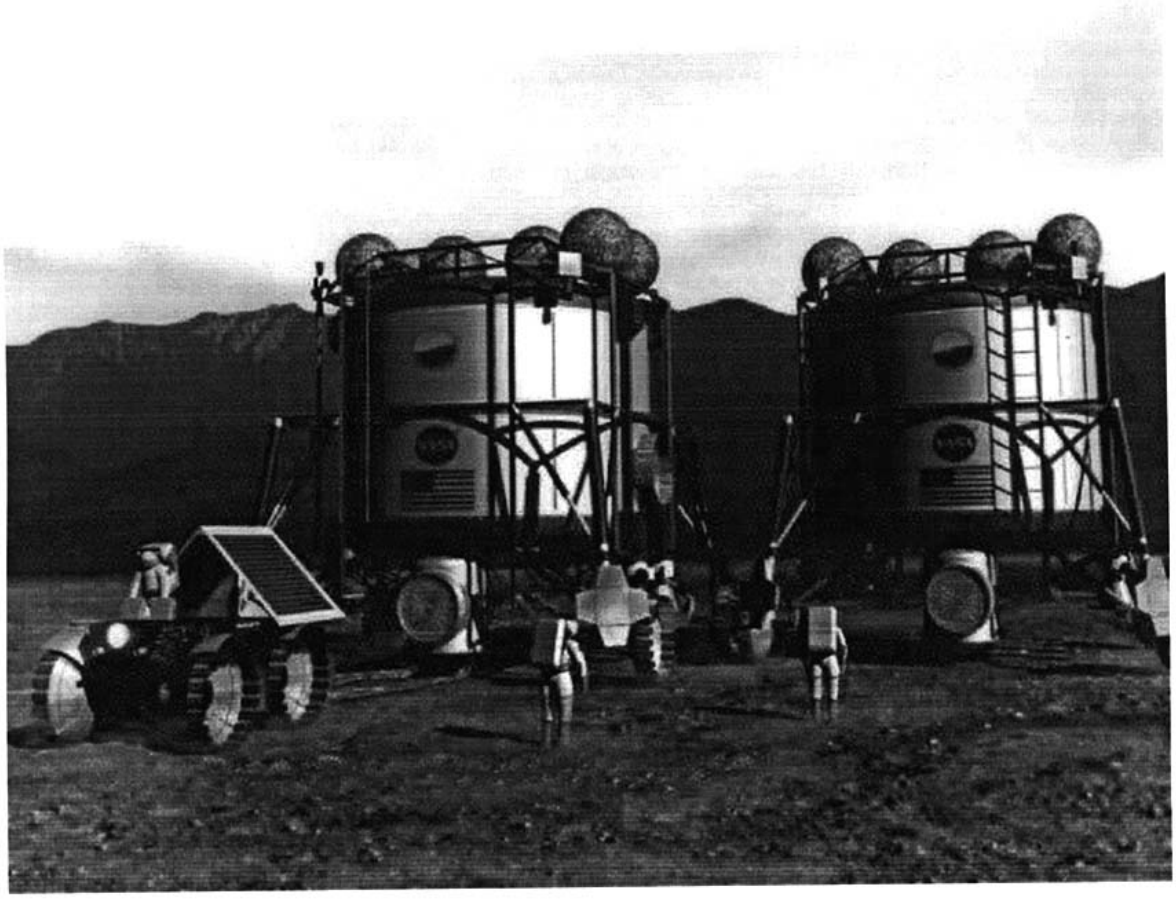
bubble models. A bubble model is a generic term that identifies any system of equations that describe bubble growth and resolution. These models can be simple or complex, and are often used to associate theoretical bubble growth with observed outcomes from various decompressions. Notice that the $O_2$ partial pressure for Option 1 is slightly hypoxic at 77 mmHg, normally at 100 mmHg with 98% hemoglobin saturation (see Fig. 1). However, humans can adapt and compensate over the course of a chronic exposure (9,26).

***Table II. Metabolic and Inert Gases in Option 1***

| Gas | Partial Pressure in Lung (mmHg) | Partial Pressure in Tissue (mmHg, using mixed venous blood) |
|---|---|---|
| $O_2$ | 77 | 40 (4 vol. % extraction) |
| $CO_2$ | 40 | 45 |
| $H_20$ | 47 | 47 |
| Ar | 93 (1.80 psia) | 93 (1.80 psia) |
| $N_2$ | 157 (3.03 psia) | 157 (3.03 psia) |
| total pressure | 414 (8.0 psia) | 384** |

* application of the alveolar oxygen equation using acute exposure conditions

** lower pressure in tissue than ambient pressure is due to differences in $O_2$ consumption and $CO_2$ production, and solubility differences of these gases in tissue



***Extravehicular activity near the Mars habitat.***

Courtesy of the Mars Society Web Page:
www.marssociety.org, October 1999.

## Inert Gases: Ar or $N_2$ in a Binary Gas Mixture

Table III shows several physical characteristics (3) of gases present in the Mars habitat, and are used as input constants in efforts to model bubble growth.

Burkard and Van Liew (3) have described key variables involved in bubble growth. The solubility of a gas in a tissue determines the upper limit on the volume that can be evolved after decompression, while solubility of a gas in the blood determines the rate of gas molecules entering or leaving the tissue by blood flow. For perfusion-limited exchange, the partition coefficient determines the rate of partial pressure change by washout (gas removal) from tissue via blood. Finally, the permeation coefficient determines the rate of transfer of a gas from the tissue to the bubble.

The body is composed of various types of tissue. This evaluation is confined to lipid and lean tissues. Lipid tissue includes the nervous system and fat while lean tissues are muscle and water. The contribution of cartilage, tendons, bone, and all the rest, toward body mass are lumped into both lipid and lean components. I assume that a discussion about gas content and bubble growth in lipid is a worst-case condition from which to develop conservative recommendations about the breathing gas for a Mars habitat. The two characteristics that show large differences in lipid between $N_2$ and Ar are solubility and permeation coefficients (see Table III). Ar is about twice as soluble as $N_2$, so for the same equilibrium, partial pressure there is twice the amount of Ar. Ar is about twice as permeable as $N_2$, so for the same partial pressure gradient across the tissue-bubble interface the rate of transfer of Ar from the tissue to the bubble is doubled.

From Burkard and Van Liew (3), the peak volume of a bubble in a low bubble density simulation (1 bubble/ml tissue) is proportional to the ratio of the permeation coefficient to the partition coefficient, with the ratio taken to a power of 1.5. Figure 2 from ref. 3 shows that the peak volume is about 2.5 times greater for an Ar - $O_2$ mixture compared to an $N_2$ - $O_2$ mixture, using the values for $N_2$ and Ar in lipid. The duration of a bubble is proportional to one over the partition coefficient, so a bubble will persist just a little longer for Ar than $N_2$.

This report is limited to an analysis and discussion of the low bubble density case (28) since hypobaric decompressions are more likely to initiate growth of a few large micronuclei rather than many smaller nuclei as in the case of hyperbaric decompressions. A detailed discussion about micronuclei is beyond the scope of this report.

***Table III. Physical Characteristics of Gases***

| | **Nitrogen** | **Argon** | **Oxygen** | **Carbon Dioxide** |
|---|---|---|---|---|
| molecular weight | 28 | 40 | 32 | 44 |
| Solubility ($\alpha$), $ml * ml^{-1} * (100\ kPa)^{-1}$ | | | | |
| In blood | 0.0146 | 0.0289 | 0.0227 | 2.35 |
| In lipid | 0.0615 | 0.131 | 0.110 | 1.15 |
| Diffusivity (D), $cm^2$ / min | | | | |
| In water | $1.32 * 10^{-3}$ | $1.11 * 10^{-3}$ | $1.24 * 10^{-3}$ | $1.05 * 10^{-3}$ |
| In lipid | $6.02 * 10^{-4}$ | $5.05 * 10^{-4}$ | $5.64 * 10^{-4}$ | $4.80 * 10^{-4}$ |
| Partition coefficient, (unitless, ratio of solubilities) | | | | |
| Blood/lipid | 0.237 | 0.220 | 0.206 | 2.043 |
| Permeation coefficient ($\alpha * D$) | | | | |
| In lipid | $3.70 * 10^{-5}$ | $6.61 * 10^{-5}$ | $6.20 * 10^{-5}$ | $5.80 * 10^{-4}$ |

A word about pressure units. Pressure will be discussed in terms of mmHg, psia, and kPa (kilopascals). There are 51.7 mmHg / psia, and 101.32 kPa equals 14.7 psia. Expressing pressure in terms of feet altitude or feet sea water is avoided.

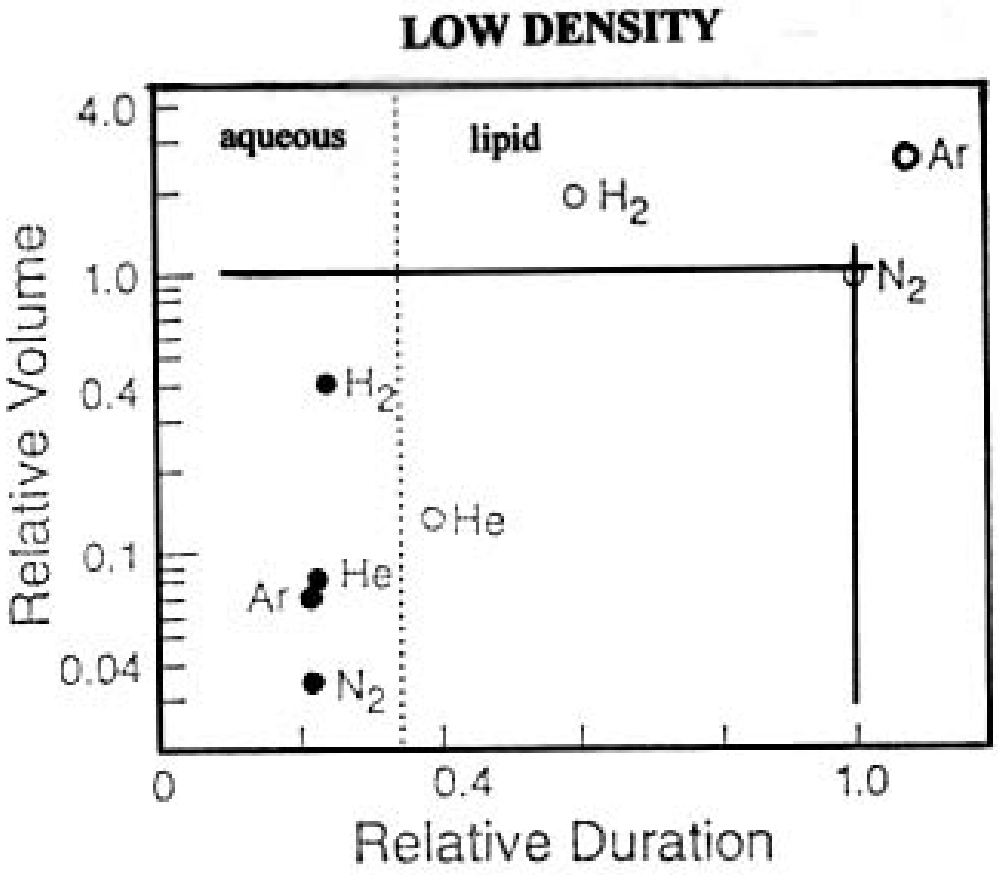



***Figure 2. For a specific saturation dive and relative to $N_2$ in lipid tissue, a bubble containing Ar would grow larger and last longer in both aqueous and lipid tissue in a simulation of low bubble density. The same trend is evident in a simulation of high bubble density (not shown, and see ref. 3 for additional details about the simulations). A conclusion is that Ar is not an ideal component of the breathing mixture in the Mars habitat if bubble growth and persistence are to be avoided after decompression to 3.75 psia.***

## Binary Gas Mixtures in Animal Decompressions

Scientists (16,17) decompress small animals such as mice and rats after saturation or nonsaturation exposures to various inert gases to study the mechanisms of gas bubble formation and DCS. They study the transportation of gases and the influence of their physical properties on the outcome of decompressions. From Lever's data (17), the mean onset time to DCS in mice increases as the water-to-fat partition coefficient decreases in the order: nitrous oxide ($N_2O$), helium (He), Ar, $N_2$, carbon tetrafluoride ($CF_4$), and finally sulfur hexafluoride ($SF_6$). For example, the mean DCS onset time after a nonsaturation exposure to Ar with a 0.185 partition coefficient was about two min compared to about 16 min for $SF_6$ with a 0.0159 partition

coefficient. The gas quickest into the tissue, even if not very soluble, has the potential to cause the most damage from a nonsaturation dive (17).

For saturation exposures, the reverse relationship will apply. Once in the lipid tissue, $SF_6$ would tend to remain and release a tremendous volume of gas compared to the Ar case. The author (17) concluded that the most relevant single factor to describe the supersaturation limit associated with 50% DCS in mice was the amount of inert gas dissolved in lipid tissue. Mice breathing $SF_6$ would produce 50% DCS after a decompression from a saturation exposure to about 60 psi to 14.7 psi while mice exposed to He tolerated about a 200 psi decompression to produce the same 50% DCS. The supersaturation limit was lower for Ar at 110 psi compared to 170 psi for $N_2$. These experiments were compromised by the fact that some inert gases act as anesthetics under hyperbaric conditions. In recent studies, it was concluded that DCS risk in rats and guinea pigs were not simply proportional to the lipid solubility of the inert gas (18,19). Other characteristics of the inert gases, and interactions with metabolic gases had to be considered.

## Inert Gases: Ar and $N_2$ in a Trinary Gas Mixture

The case for a trinary breathing mixture, $O_2$ plus two inert gases, is even more complex, and a bubble model is a useful tool to evaluate combinations of variables. Published examples by Burkard and Van Liew (2,30) concerned He and $N_2$ in diving, but are instructive in the case of Ar and $N_2$ on Mars. Figure 3 from ref. 30 shows peak bubble volume in the low bubble density case from a normoxic saturated diver decompressed from 2 ATA to 1 ATA breathing a 50–50 mixture of He and $N_2$. A normoxic breathing mixture is one in which the partial pressure of $O_2$ is constant at 0.21 ATA. A bubble in aqueous tissue increases volume 1.5 times relative to a dive with only $N_2$, and increases volume 2.5 times if the breathing gas were only He. Clearly, He dissolved in aqueous tissue is not a desirable situation. In lipid tissue, there is an opposite effect. A bubble from a 50–50 mixture of He and $N_2$ has only 1/3 the volume relative to a dive with only $N_2$. The bubble is 1/10 the volume if the breathing gas were only He. Nitrogen dissolved in lipid tissue is not the best option. There appears to be an advantage of a trinary mixture in saturation diving if DCS is associated with a “mixed tissue.” Other model “systems” are also available to evaluate trinary mixtures (12,27).

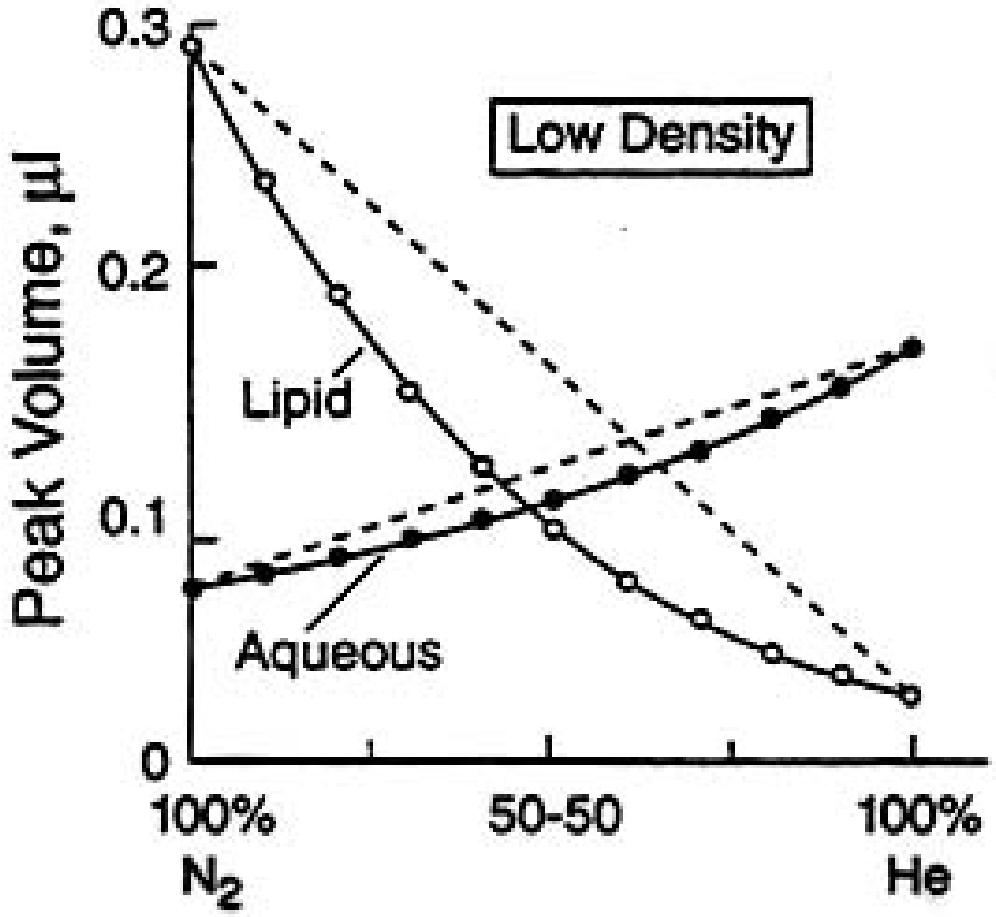



***Figure 3. Peak bubble volume in aqueous and lipid tissues following a 200- to 100-kPa decompression after saturation with a normoxic $N_2$–He breathing mixture in a simulation of low bubble density. The peak bubble volume is smaller in the trinary simulations than a linearly interpolated mid-point (dashed line) between the sizes of bubbles with $N_2$ alone and with He alone (see ref. 30 for additional details about the simulations). If DCS were caused by bubble growth in aqueous tissue, then $N_2$ alone would be best. But if DCS were caused by bubble growth in lipid tissue, then He alone would be best. It seems likely that DCS is caused by bubble growth in a "mixed tissue," therefore a trinary gas mixture has advantages.***

A similar qualitative pattern would occur if He were replaced with Ar. Since $N_2$ falls between Ar and He in the magnitude of the physical properties, the Ar would behave as the $N_2$ did (a dominant contribution in lipid tissue) and the $N_2$ would behave approximately as the He did (a dominant contribution in aqueous tissue compared to Ar). However both Ar and $N_2$ have properties that make them worse compared to He in a saturation exposure, so any further assessment of an Ar–$N_2$ trinary mixture must yield to a bubble model. The above summary speaks to the complex conditions present with a trinary mixture. Also, as described below,

hypobaric decompressions have unique outcomes because about 50% of the bubble is metabolic gas, while in the diving case the contribution of metabolic gases ($O_2$, $CO_2$, and water vapor) toward bubble growth and DCS might be ignored.

## Trinary Gas Mixtures in Animal Decompressions

Lillo's (18) figure, reproduced here as Fig. 4, shows the probability of death in rats decompressed from saturation depths of either 175 or 200 feet sea water (fsw) as a function of the Ar concentration in the breathing mixture. The curves to the left of the vertical arrow cover the range of Ar concentrations envisioned for the Mars habitat. The curves have the steepest slopes in this range. However the absolute pressure of Ar in the tissues of rats is about 25 psia at 200 fsw and only about 1.8 psia for humans under Option 1 in Table II. Figure 4 is just to reiterate that Ar plays a significant role in the outcome of decompressions, at least in rats decompressed from hyperbaric exposures.

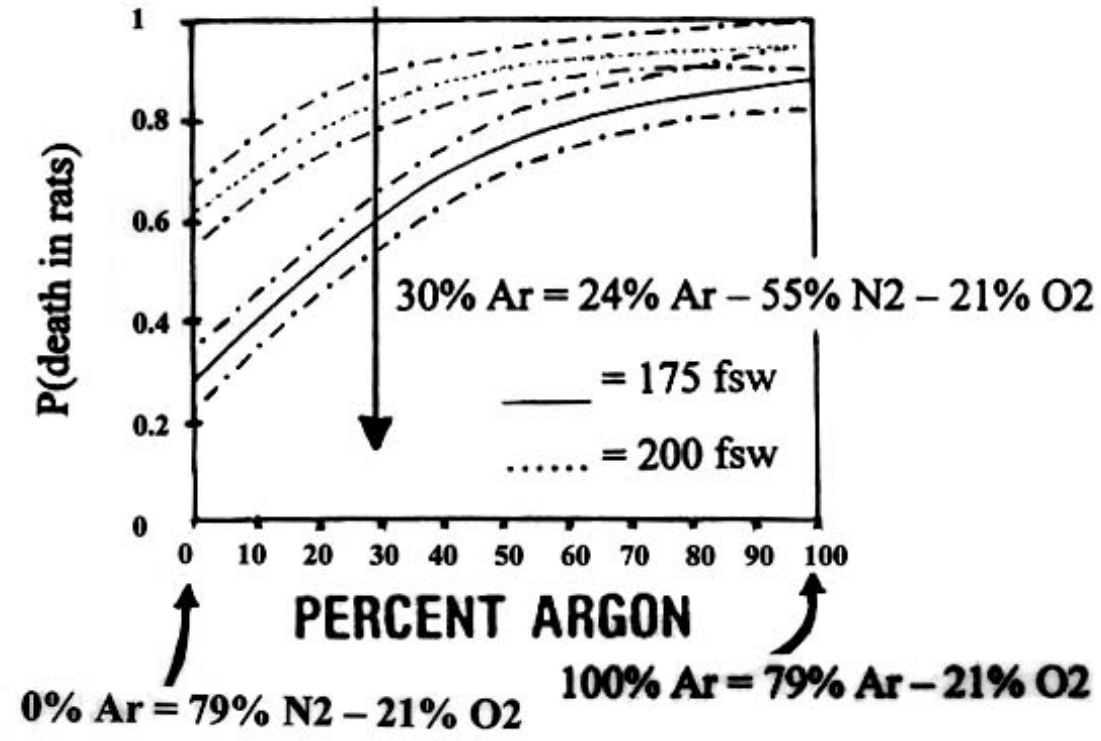



***Figure 4. The P (death in rats) as a function of hyperbaric saturation pressure, expressed as feet sea water, and the concentration of Ar in a trinary breathing mixture that includes $N_2$. 100% Ar on the x-axis means that Ar was the only inert gas with 21% $O_2$. The 30% Ar example, shown with the vertical arrow, means the breathing gas has 24% Ar – 55% $N_2$ – 21% $O_2$.***

## Metabolic Gases

Oxygen and $CO_2$ are present in the tissue and blood, both dissolved and loosely bound to hemoglobin, and participate in reversible reactions that form part of the acid-base system. The total amounts of these gases are substantial, but due to metabolism, are only transiently in excess in the body when there is decompression to a lower pressure. In other words, physiological controls keep the partial pressure of metabolic gases constant in the body. Oxygen has about the same solubility as Ar, and in the hypobaric case there is no storage of $O_2$ in the tissues. Oxygen delivery is exquisitely linked to tissue metabolism. Since the pressures of $O_2$, $CO_2$, and $H_20$ (water vapor) are held constant over the useful range of hypobaric pressures, their fractions in bubbles are inversely proportional to pressure, as seen in Fig. 5 from ref. 29.

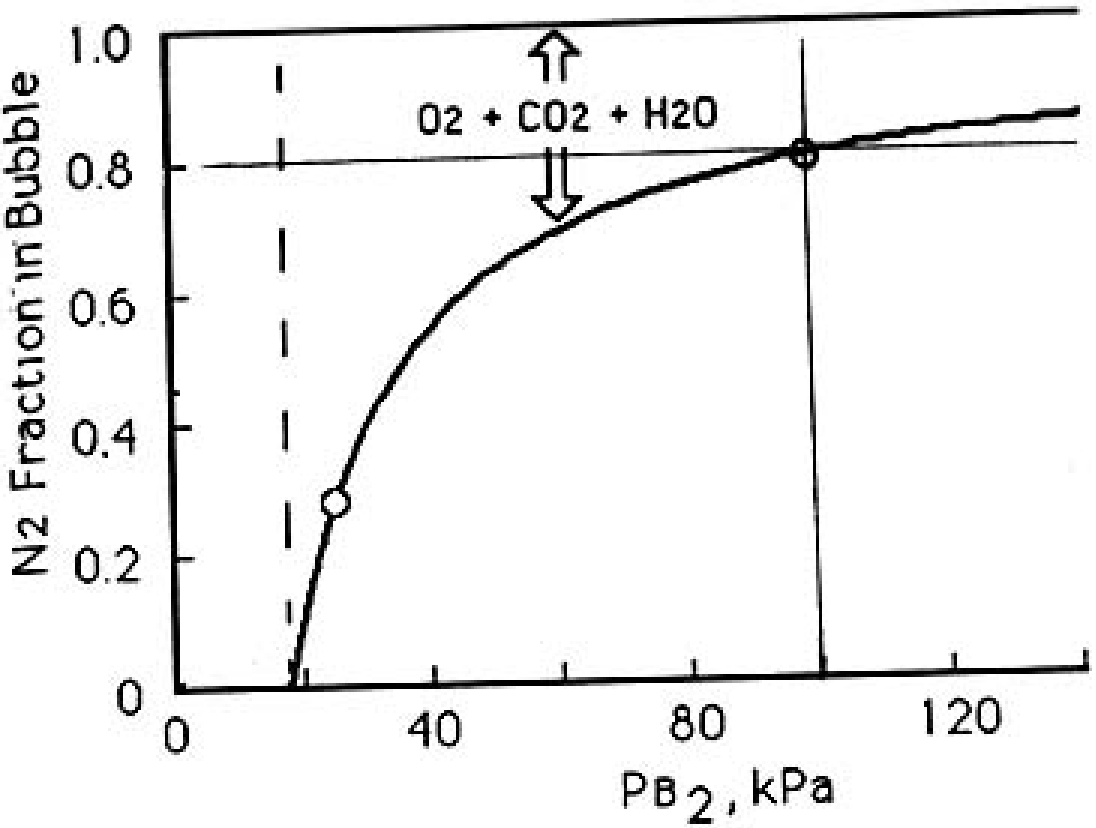



***Figure 5. The presence of constant metabolic gas pressures ($O_2$, $CO_2$, and $H_20$ vapor) and the rapid equilibration of pressure across the tissue-bubble interface means that the fraction of any inert gases, only $N_2$ in this case, decrease as ambient pressure decreases.***

About 60% of the body weight is water, 48 l (liters) for our "standard" 80-kg subject of which 22 l are extracellular and 26 l are intracellular. The body is essentially "wet" at 37°C, which always provides for 47 mmHg of water vapor pressure. There is not enough counter-

pressure to keep our body fluids in a liquid state outside a space suit due to the low atmospheric pressure on Mars, about 5 mmHg. The medical term for this deadly situation is ebulism.

## Tissue Ratio and Hypobaric DCS Risk

Fundamental to understanding the risk of DCS is to first understand how a simple decompression "dose" called the tissue ratio (TR) is calculated. TR is the ratio of inert gas pressure in the tissue to ambient pressure, specifically the ratio of $P1N_2$ to P2 when only $N_2$ and $O_2$ are considered. $P1N_2$ is defined in Eq. 4 and P2 is the ambient pressure (or suit pressure) after ascent. Prebreathing 100% $O_2$ or $O_2$-enriched mixtures before a hypobaric decompression is often used to prevent DCS, so it is necessary to account for the use of $O_2$-enriched mixtures before decompression. Following a change in $N_2$ partial pressure in the breathing mixture, such as during a switch from ambient air to a mask connected to 100% $O_2$, the $N_2$ partial pressure that is reached in a designated tissue compartment after a specific time is:

$$P1N_2 = P_0 + (P_a - P_0)\,(1 - e^{-k\,t}), \qquad (4)$$

where $P1N_2$ is the calculated $N_2$ partial pressure in the tissue after "t" mins, $P_0$ is the initial $N_2$ partial pressure in the compartment, $P_a$ is the ambient $N_2$ partial pressure in breathing mixture, and "t" is the time at the new $P_a$ in minutes. The tissue rate constant "k" is equal to $\ln(2)/t_{1/2}$, where $t_{1/2}$ is the half-time for $N_2$ partial pressure in the 360-min compartment. In some applications, the initial equilibrium $N_2$ pressure ($P_0$) in the tissue at sea level is taken as 11.6 psia instead of an average alveolar (therefore tissue) $N_2$ pressure of about 11.0 psia. The use of dry-gas, ambient $N_2$ pressure as equilibrium tissue $N_2$ pressure ($P_0$) and as the $N_2$ pressure in the breathing mixture ($P_a$) makes the application of Eq. 4 simple, but in some examples I will use estimates of the inert gas pressures in tissues when defining TR.

It has been observed that, given two exposures with the same TR, the DCS risk is greater for the case where ambient pressure was lower (4,5). Consider two decompressions. The first is with 5.0 psia of $N_2$ in the tissue before an ascent to 3.75 psia, the ratio of pressures is 1.33. The second with 5.7 psia of $N_2$ in the tissue before an ascent to 4.30 psia, also a ratio of 1.33. All else being equal, one might conclude that the DCS risk would be the same. In a physical system, the total evolved gas given infinite time would be identical between the two examples above (22). However TR is not closely related to bubble size since the presence of metabolic gases will cause

bubbles to grow larger at lower ambient pressure (29). This is seen in an equation by Van Liew (29) that relates the total volume of evolved gas expressed at ambient pressure to TR.

$$\Delta V_{(a)tot} = \alpha N_2 * V_{tis} * Ps * [(TR / FN_2) - 1 ], \quad (5)$$

where $\Delta V_{(a)tot}$ is the total volume (ml) of evolved gas in a bubbles, expressed at ambient pressure, $\alpha N_2$ is solubility of $N_2$ in tissue, $V_{tis}$ is volume (ml) of tissue available to a bubble, Ps is standard pressure, TR is the ratio of tissue $N_2$ pressure to ambient pressure ($PtisN_2/P_B$), and $FN_2$ is the fraction of $N_2$ in a bubble.

As the total pressure decreases, the fraction of $N_2$ ($FN_2$) in a bubble must decrease due to the presence of a constant metabolic gas pressure in the bubble. Notice that as $FN_2$ decreases as ambient pressure decreases, the total evolved volume increases given the same TR. In the above case with a constant TR of 1.33 but two different ambient pressures, the total evolved volume at 3.75 psia is about 1.8 times larger than at 4.3 psia.

## DCS Risk Associated With Simple Tissue Ratio

TR appears in bubble models (12,27,29) as well as in empirical models (5,7). A biophysical description of TR as it applies to evolved gas is available (6,29). It is instructive to show how TR is associated with the risk of hypobaric DCS through a probability model. This effort demonstrates the central role of TR, the contribution of metabolic gases, and the introduction of a variable called adynamia (8,24). All three variables are important to discuss the risk of DCS on Mars.

Figure 6 shows the probability of DCS [P(DCS)] over a narrow range of TR. TR is just one variable in an expression of DCS dose defined by Eq. 6.

$$Dose = [\ln (1 + (((P1N_2 + c1) / P2) - 1)^{c2} * (1 + (c3 * exercise)) * (t * \rho)^{\lambda})], \quad (6)$$

where ln is the natural log, $PIN_2$ is computed $N_2$ pressure (see Eq. 4), constant c1 is 1.563, P2 is ambient pressure, suit pressure in our case, as psia after the decompression, constant c2 is 4.366, constant c3 is 1.578, exercise is either one if there is exercise planned during the extravehicular activity (EVA) or zero if there is no exercise planned, t is the time of the EVA as hrs, constant $\rho$ is 0.063, and finally constant $\lambda$ is 1.521.

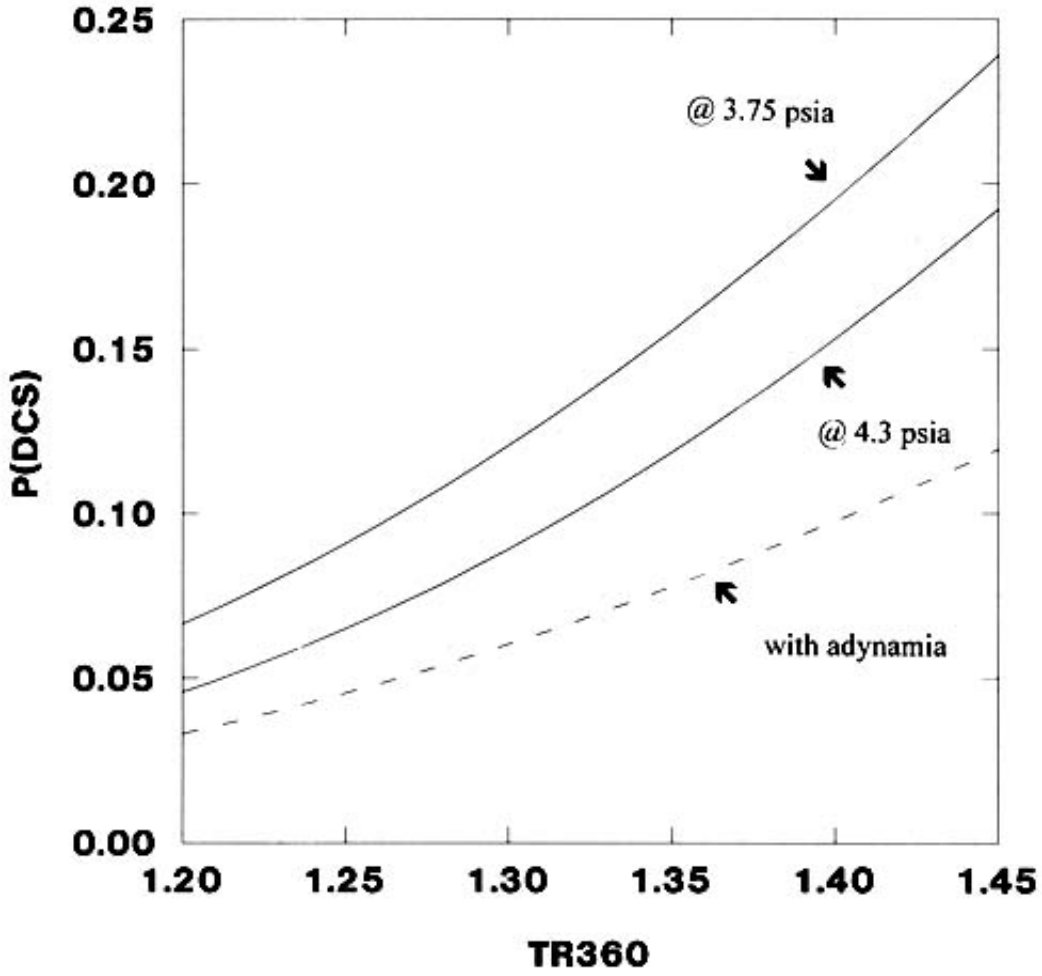



***Figure 6. The P(DCS) for a given TR360 (TR based on a 360-min half-time compartment) is greater at 3.75 psia compared to 4.3 psia in a simulation where exercise is present during a 6-hr exposure. Adynamia is not a variable in the probability model, so ½ the risk at 3.75 psia is used to approximate the contribution of adynamia. On Mars, an 82-kg man with 45 kg of space suit and equipment would weigh about 48 kg. Exercise during a hypobaric exposure is known to increase the risk of DCS, but it is not known how the "effective" exercise on Mars would influence the risk of DCS.***

Equation 7 is then used to compute the P(DCS) given $P1N_2$, P2, the exercise condition (1 or 0), and the time spent at P2.

$$P(DCS) = 1 - \exp^{-Dose}. \quad (7)$$

The curve marked "@3.75 psia" on Fig. 6 has the highest P(DCS) for a given TR compared to the other two curves. The constant c1 (and the constants c2, c3, $\rho$, and $\lambda$) in Eq. 6 was statistically derived by optimizing the probability model (Eq. 7) to 1075 altitude

decompression records (5). The location of the constant c1 in the numerator of the TR expression is where the contribution of metabolic gases would be added in a bubble model. For the same two TRs where the denominators are different, the presence of the constant c1 in the numerator means the ratio with the smallest denominator will be the largest. This is easily seen with an example: ratio $\alpha = (12 + 3)/6 = 2.5$, ratio $\beta = (6 + 3)/3 = 3.0$, where the TR of 12/6 and 6/3 both equal 2.0, but ratio $\beta$ is greater than ratio $\alpha$. The inclusion of the constant c1 to TR makes a better expression of DCS dose than TR alone over a larger range of P2.

For the above reason, the curve marked "@ 3.75 psia" gives a slightly greater P(DCS) compared to the curve marked "@ 4.3 psia." The difference between 4.3 psia and 3.75 psia (0.55 psia) may not appear significant, but recall that all dissolved gases will evolve out of the body as it approaches a vacuum. The other two variables in the simulation, exercise coded as one and exposure time of 6 hr, are the same for each curve. The difference between the curves increases from 2% at a TR of 1.2 to 4.6% at a TR of 1.45. In other words, it is much riskier to do a 6-hr exposure with exercise at 3.75 psia compared to 4.3 psia at a higher TR than at a lower TR. Finally, the curve marked "with adynamia" is simply ½ the risk at 3.75 psia to provide a "guess" about the risk of DCS on Mars as a function of TR.

Adynamia is a concept about reducing the risk of DCS in the lower body by reducing the exercise, particularly walking, in the lower body before and during the decompression (24). Since walking is such a natural event, it is often overlooked as a form of exercise in research on DCS. It might be acceptable to overlook walking as exercise in Earth-based applications that include a lot of walking, but this detail must not be overlooked when applying DCS results collected on Earth to astronauts during EVA. Lower body movement in space "walking" is very different than walking on Earth, and walking on Mars will be different than walking on Earth due to $3/8^{th}$ the force of gravity relative to Earth. The concept of "effective" exercise on Mars will have to be better understood before we can extrapolate what we know about DCS on Earth to what we predict about DCS on Mars (14). The reduction of risk by ½ in my example is a reasonable guess at low TRs based on a recent analysis (8).

## Simple Inert Gas Mass Balance

Given an 80-kg person with 20% body weight as lipid (both fat and nervous system), what is the available volume of inert gas in the tissue at the time of decompression under Option

1 in Table II? I will show that this dissolved volume is about 880 ml. The volume is expressed at 100 kPa and 37°C, and is how solubility in Table III is expressed.

Gas solubility is expressed in terms of tissue volume. To calculate the volume of gas dissolved in a volume of tissue, first convert body mass to body volume. Lean tissue has the same density of water (1 kg/l), so 80% of 80 kg is 64 l of lean tissue. Lipid tissue is less dense than water (about 0.9 kg/l), so 20% of 80 kg is 16 kg of lipid mass, but closer to 17.6 l of lipid volume. Table IV shows the volume of inert gases in the tissues from Option 1 available to form bubbles on a subsequent decompression: 482 ml for Ar and 397 ml for $N_2$. The total of 879 ml compares to 1440 ml for the same person breathing air at sea level (calculations not shown).

***Table IV. A Simple Mass Balance at 8.0 psia***

| | Pressure (ATA) | Lipid $\alpha$ (ml/ml*100kPa) | Volume (ml) | Lean $\alpha$ (ml/ml*100kPa) | Volume (ml) |
|---|---|---|---|---|---|
| Ar | 0.122 | 0.131 | 281 | 0.0258 | 201 |
| $N_2$ | 0.206 | 0.0615 | 223 | 0.0132 | 174 |
| Totals | 0.33 ATA (4.88 psia) | | 504 | | 375 |
| Grand total @ 8.0 psia (0.54 ATA) | | | | | 879 |

If I assume that a TR of 1.30 is safe, just a conservative guess based on past experience, for an unlimited exposure to 3.75 psia on Mars, then the inert gas pressure in the tissues cannot exceed 4.87 psia, since 4.87/3.75 = 1.30. A caveat is that TR = 1.30 may be reasonable from a Type I "pain-only" DCS perspective, but the use of Ar may predispose a person to a greater embolic risk due to the high solubility in lipid tissue (21). Table II shows that the total inert tissue pressure is 4.83 psia for Option 1, so it follows that an EVA can be done without $O_2$ prebreathing. Figure 7 shows the location of the summed $N_2$ and Ar pressures in the tissue and the required prebreathe time to have a TR = 1.30, zero min in this case. Any operational period of prebreathing for suit purge, leak check, and decompression (maybe 30 min) would be additional safety margin.

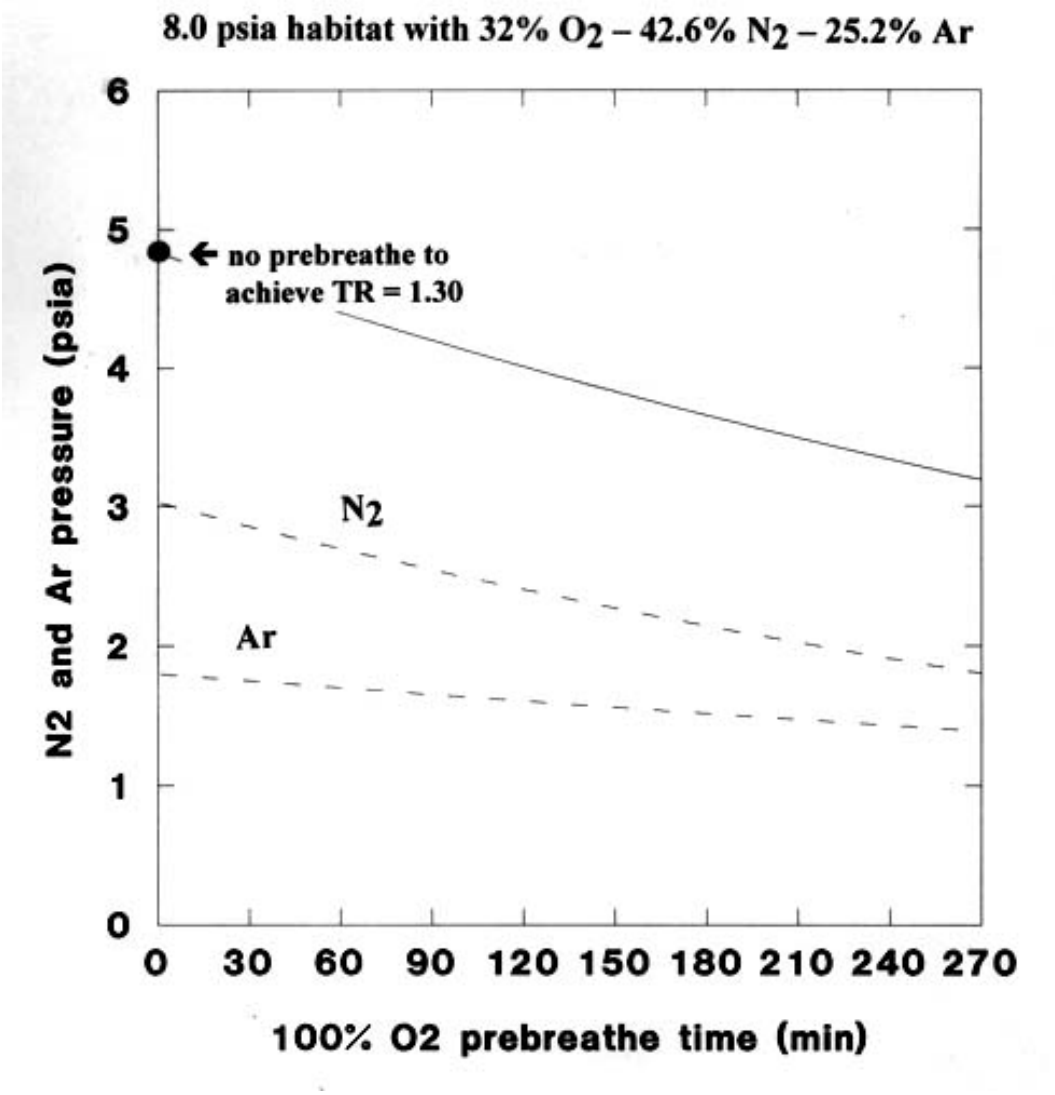



***Figure 7. Estimated total inert gas pressure (solid line) after summing the pressure of $N_2$ in the 360-min half-time tissue compartment and the Ar pressure in the 720-min half-time tissue compartment. Notice that no prebreathing is required before the EVA since the TR is already 1.29 (4.83 psia total tissue pressure/3.75 psia suit pressure). This ASSUMES that an EVA to 3.75 psia with a TR of 1.30 from a trinary gas mixture is safe.***

## Oxygen Prebreathing

The situation is different for Options 2 and 3 since the total inert tissue pressure is 5.69 psia and 6.59 psia, respectively (see Table I). Additional inert gas removal by breathing 100% $O_2$ must occur for Options 2 and 3. The time of the prebreathe is computed, given assumptions about the removal rate for $N_2$ and Ar. If I assume that a 360-min $t_{1/2}$ and 720-min

$t_{1/2}$ describe the removal of $N_2$ and Ar, then the time needed to decrease the combined $N_2$ and Ar tissue partial pressure from 5.69 psia at 9.0 psia to 4.87 psia to achieve a 1.30 TR using 100% $O_2$ prebreathe is 100 minutes. Equation 8 was solved iteratively for the correct time given the initial equilibrium tissue pressure for $N_2$ and Ar, and that the total inert gas pressure in the tissue could not exceed 4.87 psia.

$$\text{inert gas tissue pressure (psia)} = P1N_2 * \exp(-k_1 * t) + Ar * \exp(-k_2 * t), \quad (8)$$

where $P1N_2$ is the $N_2$ pressure in the tissue at 9.0 psia (3.58 psia), $k_1$ is the decay constant for $N_2$ = ln 2/360 = 0.001925, Ar is the Ar pressure in the tissue at 9.0 psia (2.11 psia), and $k_2$ is the decay constant for Ar = ln 2/720 = 0.0009627. Equation 8 is appropriate only when 100% $O_2$ is used, which provides for the maximum pressure gradient to remove the gases. Figure 8 shows the decrease in $N_2$ and Ar pressure during a 4.5-hr prebreathe with 100% $O_2$. After 100 min, the ratio of total pressure (4.87 psia) to suit pressure (3.75 psia) provides a TR = 1.30. Option 3 requires a 195-min prebreathe, as seen in Fig. 9.

The decay constants $k_1$ and $k_2$ can be defined in physiology terms that involve the partition coefficient and blood flow. For the general case of the ith inert gas:

$$k_i = \alpha bl_i * Q / \alpha tis_i, \quad (9)$$

where $k_i$ has unit of $min^{-1}$, $\alpha bl_i$ is solubility of gas in blood, Q is blood flow as ml blood/ml tissue/min, and $\alpha tis_i$ is solubility of gas in tissue. For the case of Ar, to achieve a half-time of 720 min and using the blood/lipid partition coefficient for Ar in Table III, the blood flow through one ml of fat tissue would need to be 0.0044 ml/min, about five times lower than blood flow through fat tissue (0.02 ml/min/ml fat). The need for long half-time compartments to account for $N_2$ and Ar points to the reality that the removal of tissue inert gas is a complex perfusion-diffusion process.

Before leaving this section, and diverting slightly, the topic of exercise during prebreathe should be discussed as a practical means to accelerate inert gas removal from the tissues before decompression. The available blood volume in a person at rest cannot be distributed into all capillaries at all times, but the physiological responses to exercise increase the perfusion in tissues otherwise minimally perfused. The 720- and 360-min half-times discussed in connection with Eqs. 4, 8, and 9 are based on the idea that there is no exercise during prebreathe. Equation 9 shows that as blood flow increases the $k_i$ increases, which means the half-time for inert gas removal decreases ($t_{1/2i} = \ln(2)/k_i$). The use of modest exercise during $O_2$ prebreathe to

accelerate $N_2$ removal reduces the risk of DCS (20,31), and is a procedure that should be developed for Mars EVAs. However (my opinion), the use of modest exercise just before the EVA should be considered as extra safety margin, not as an operational method to manage a risky situation at the last minute. In other words, the habitat atmosphere should allow for safe EVAs without additional "physiological" intervention from the crew.

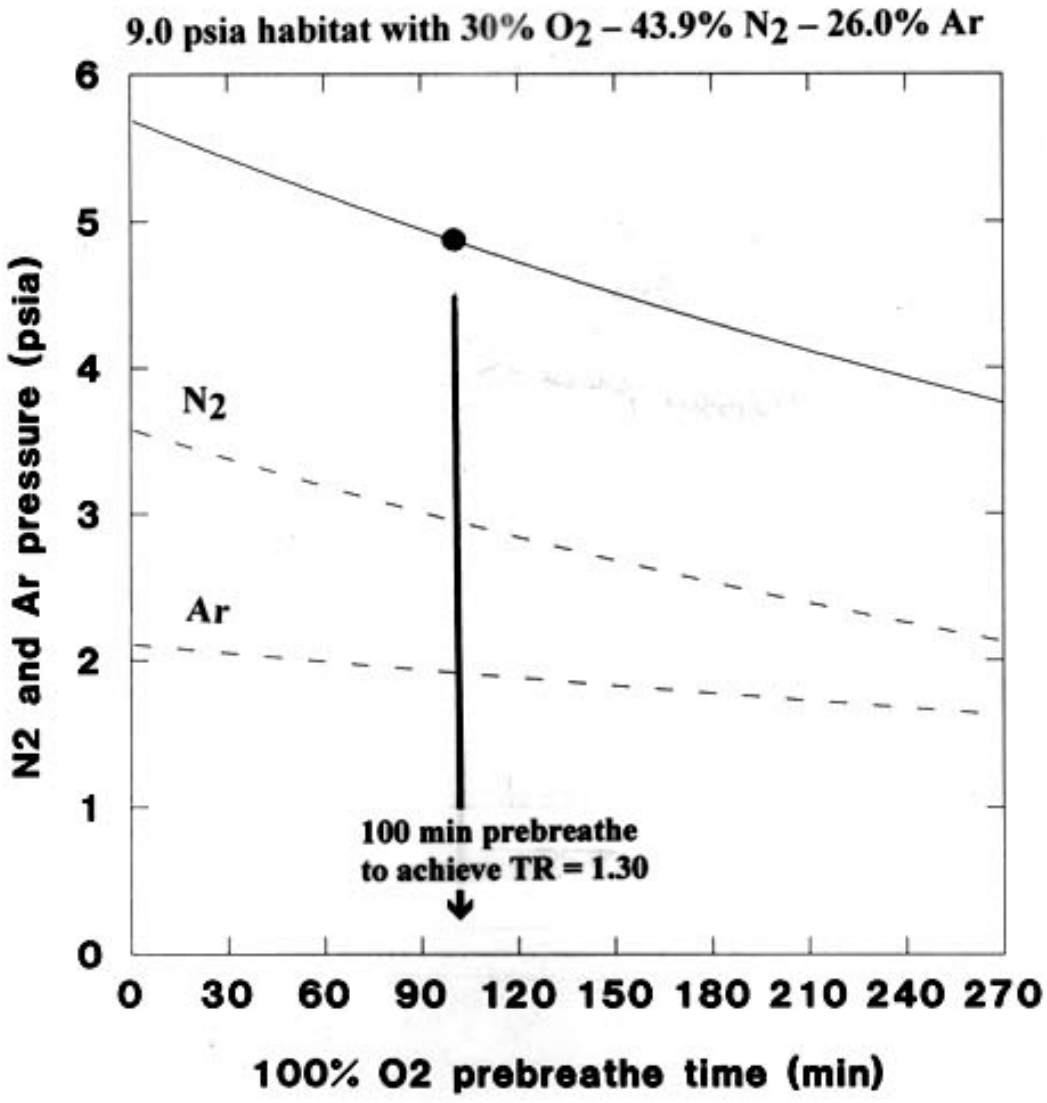



***Figure 8. Decrease in total inert gas pressure (solid line) as a function of time breathing 100% $O_2$ before EVA. The decrease of $N_2$ and Ar are not the same since the loss and gain of Ar is ASSUMED to be ½ that of $N_2$. It would take 100 min of $O_2$ prebreathing in the 9.0 psia habitat to achieve a 1.30 TR before EVA.***

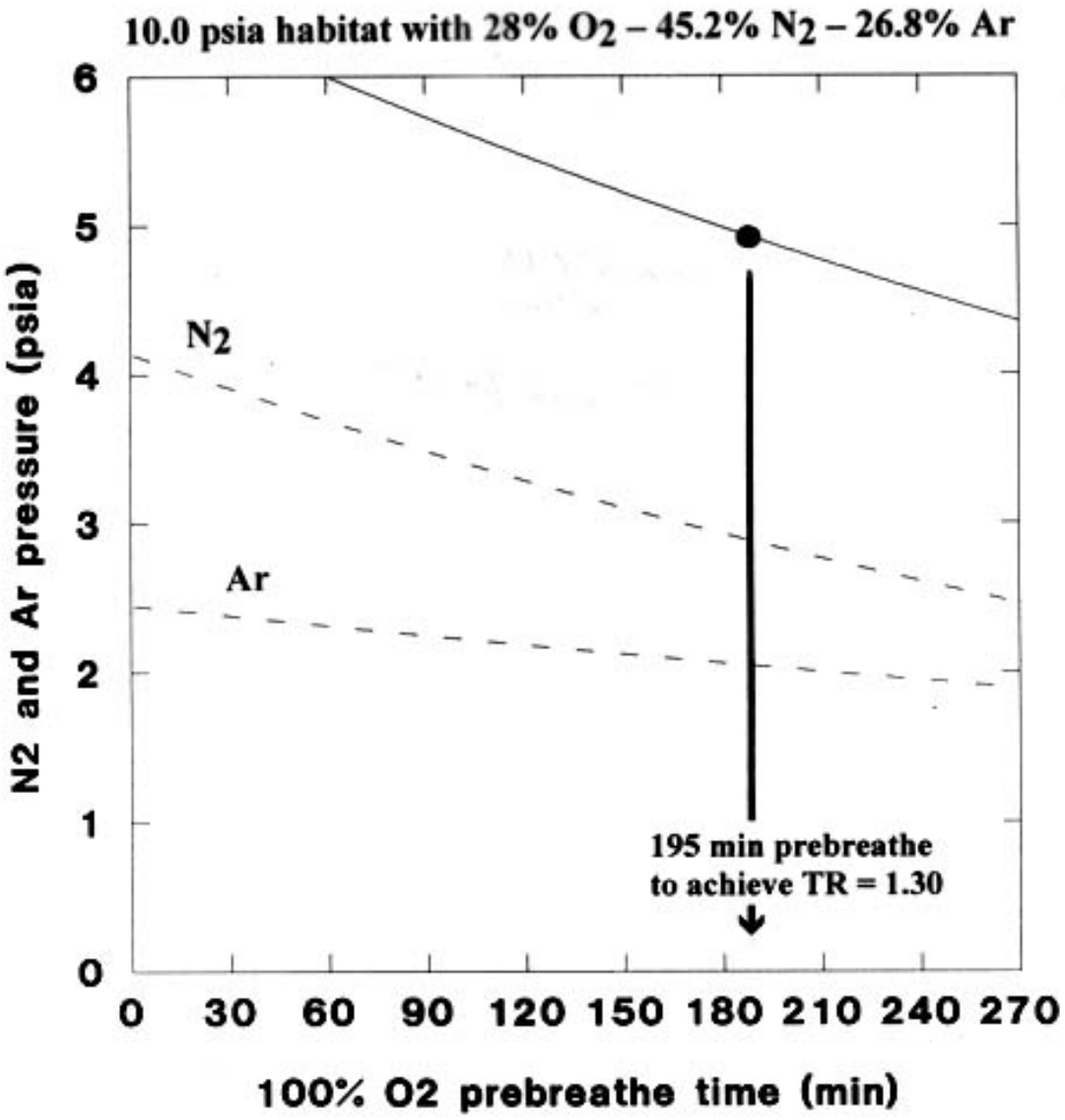



***Figure 9. Decrease in total inert gas pressure (solid line) as a function of time breathing 100% $O_2$ before EVA from the 10.0-psia habitat. It would take 195 min of $O_2$ prebreathing to achieve a 1.30 TR before EVA.***

## Potential Evolved Gas

Table V shows the volume of inert gases remaining in the lean and lipid tissues after a 100-min prebreathe with 100% $O_2$.

***Table V. A Simple Mass Balance After a 100-Min Prebreathe at 9.0 psia***

| | Volume in Lipid (ml) | Volume in Lean (ml) |
|---|---|---|
| Ar | 284 | 203 |
| $N_2$ | 225 | 176 |
| Totals | 509 | 379 |
| Grand Total @ 9.0 psia (0.61 ATA) | | 888 |

The total volume drops from 1038 ml (calculations not shown) to 888 ml due to the prebreathe. The difference in the volume of gas before the decompression to 3.75 psia and the volume of gas that will remain in solution at 3.75 psia is the volume that can undergo a Boyle's Law expansion. The volume of inert gas that will be held in solution in tissues and blood at 3.75 psia is minuscule because the pressure contribution of metabolic gases to total gas pressure in the tissue is significant. Breathing 100% $O_2$ at 3.75 psia means that the tissues will have about 2.94 psia of metabolic gas pressure (60 mmHg $O_2$, 47 mmHg $H_20$, and 45 mmHg $CO_2$). Recall that one psi equals 51.7 mmHg. The difference of 0.81 psia (3.75 – 2.94) is available for the $N_2$ and Ar, which does not convert into a large volume of inert gas held in solution, about 146 ml in our "standard" 80-kg person. Since the breathing gas in the suit has very little inert gas, these inert gas molecules would leave the body down their respective concentration gradients through the lungs without first becoming evolved gas.

The Boyle's Law expansion from standard volume (888 – 146 = 742 ml) to volume at 3.75 psia is about 963 ml:

$$V2 = P1 / P2 * V1, \tag{10}$$

where V2 is the total potential evolved volume (963 ml at P2), V1 is the initial dissolved volume (742 ml), P1 is the initial total inert gas pressure after 165 min of prebreathe (4.87 psia), and P2 is the final pressure (3.75 psia). Notice that the ratio of P1/P2 is the 1.30 TR. The evolution of 963 ml is an unrealistic situation since only a small fraction of all gas in solution will transform into evolved gas since some gas in solution will be transported out of the tissue while breathing $O_2$ at 3.75 psia. It is reasonable to assume that 20%, or about 190 ml expressed at 3.75 psia, of

gas would come out of solution in the course of an 8-hr EVA. This is analogous to an open can of soda where there is an initial release of excess $CO_2$, but even after 10 hr the soda is not "flat." $CO_2$ moves out of the soda as dissolved and evolved gas, and will continue for several hours. In other words, all of the potential for evolved gas given a particular supersaturation ($\Delta P$ = tigp – P2) is not instantaneously realized. In fact, the rate of bubble formation is proportional to the $\Delta P$ (22), in this case only 1.12 psia (4.87 – 3.75). Unfortunately, we know very little about the actual volume of evolved gas because we know very little about the formation, stability, number, or distribution of micronuclei in the tissue from which the evolved volume of gas is derived.

## Best "Guess" for DCS Risk

Figure 10 illustrates a process rather than provides accurate quantitative information on DCS risk. Figure 10 shows the compromise between DCS risk and various concentrations of Ar in the 8.0 psia habitat.

The total percentage of inert gas must be 68% since $O_2$ makes up 32% of the breathing gas at 8.0 psia. A simple rule, given my incomplete understanding of Ar in DCS risk, accounts for the contribution of Ar. My rule is needed to link the simulation to the probability model in Eq. 7 that only considers $N_2 - O_2$ breathing (5). The rule is to increase the Ar pressure in the tissue by 25%, and use 720 $t_{1/2}$ for Ar and 360 $t_{1/2}$ for $N_2$ to account for prebreathing through Eq. 8. You then add the Ar pressure to the $N_2$ pressure and use Eqs. 6 and 7 to estimate the P(DCS) as a function of Ar concentration in an 8.0 psia habitat, and other variables about the EVA. In this simulation, a 30-min prebreathe is included as part of an operational period of purge and leak checks before the EVA.

The upper curve in Fig. 10 is the estimated risk for DCS given that repetitive exercise in ambulating subjects is done. The lower curve is for the same ambulating subjects but no structure exercise is done. The contribution of exercise toward DCS risk is significant. Walking and working in the $3/8^{th}$ gravity of Mars influences the risk of DCS and, unfortunately, this important variable is not yet understood. It is likely that the better estimate of DCS risk is along the lower curve in Fig. 10, with worst-case being reflected in the upper curve. Again, Fig. 10 is just illustrative of the possible contribution of Ar toward DCS risk during EVA in a 3.75 psia suit. The absence of Ar provides for the lowest risk of between 3% and 7% while 25.2% Ar in the 8.0 psia habitat is associated with between 6% and 15% DCS.

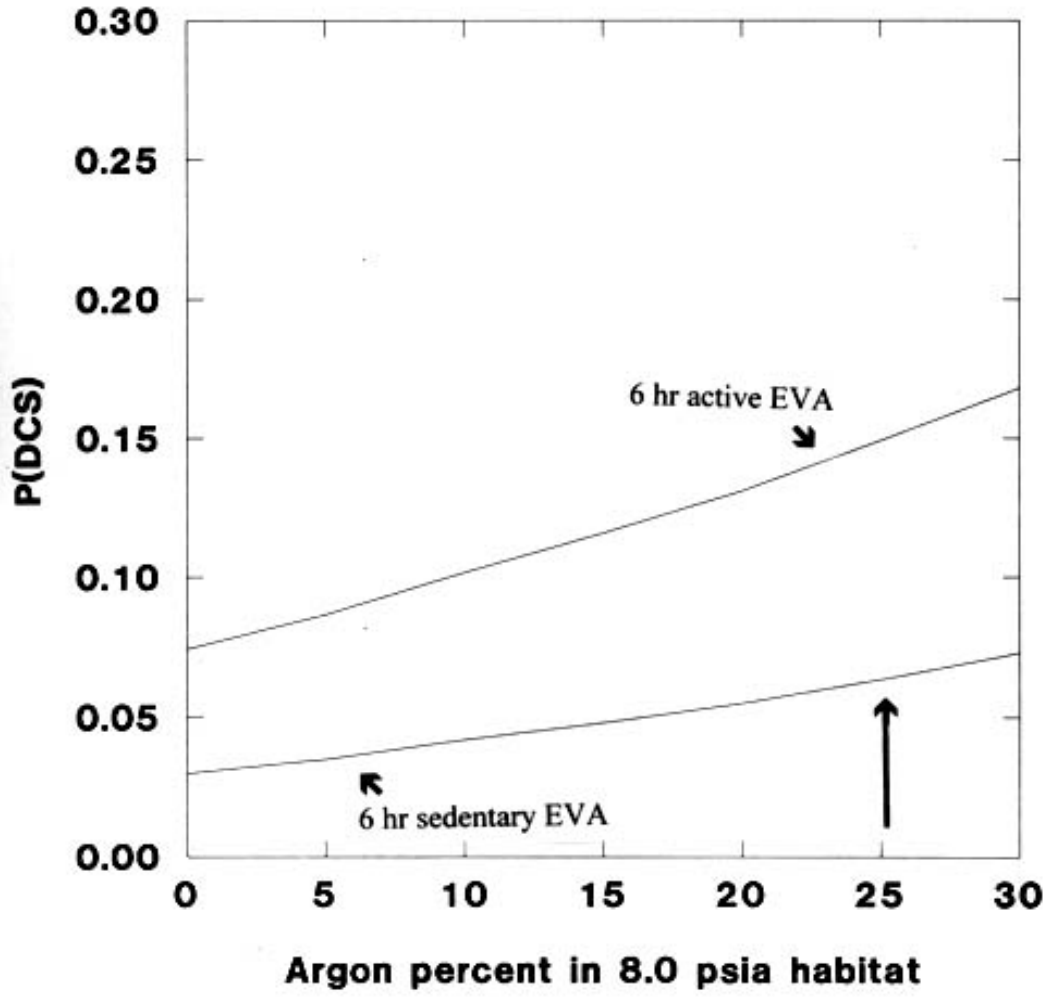



***Figure 10. Heuristic risk-to-benefit analysis of Ar as part of the breathing environment in an 8.0-psia habitat before an EVA in a 3.75-psia suit. The balance of the inert gas component is $N_2$ while the $O_2$ concentration is always 32%. The magnitude of the DCS risk depends on the two assumptions used to deal with Ar, which are suspect. It appears that the benefit of using the available 1.68 $N_2$/1.0 Ar ratio (vertical line at 25.2% Ar) is associated with some DCS risk.***

## Bubble Growth Model

A bubble growth model from Gernhardt (12,13) is available at Johnson Space Center, and it was recently compared to other models (27). As mentioned earlier, a bubble growth model is a tool often used to assess the risk of decompression by observing how a bubble(s) theoretically behaves under various simulated decompressions. The fundamental philosophy is that no bubble growth is best, but difficult to achieve even under modest decompressions. It is much better to avoid DCS than treat DCS. If one must accept conditions that cause some bubble growth, then

the philosophy is to limit growth and enhance reabsorption during the EVA, and certainly in the Rover vehicle, or back at the habitat. Table VI is the list of constants used in the model for this application.

***Table VI. Variables in Bubble Model for Low Density Case in Lipid Tissue***

| Variable | Value of the Variable |
|---|---|
| Diffusion thickness | 0.0003 cm |
| Surface tension | 30 dyne/cm |
| Tissue modulus | $2.5 \times 10^{8}$ dyne / $cm^2$ |
| Initial radius | 3 microns |
| Level | 1 min/sample |
| Linear | 0.1 ft/sample |
| $N_2$ t1/2 | 360 min |
| $N_2$ diffusivity | $1.0 \times 10^{-8}$ (lipid) $cm^2$/sec |
| $N_2$ solubility | 0.0615 (lipid) ml/ml $*$ $atm^{-1}$ |
| Ar $t_{1/2}$ | 720 min |
| Ar diffusivity | $8.41 \times 10^{-9}$ (lipid) $cm^2$/sec |
| Ar solubility | 0.131 (lipid) ml/ml $*$ $atm^{-1}$ |
| Decompression rate | 0.425 psia/min |
| Mass balance condition | yes |
| Metabolic gas | yes |
| All else | default settings |

Notice that there are several input constants, which makes this a complex simulation. Justifications, weak or strong, exist for each constant, but are not documented here. Recall that I am simulating a single spherical bubble growing in lipid tissue. The results to follow are greatly influenced by small changes in some constants. For example, an increase in surface tension from 30 to 50 dyne/cm stops bubble growth in some simulations, and changing the initial bubble (nuclei) radius greater or less than 3 microns has profound consequences on subsequent growth. An appropriate application for the model is to compare changes relative to two simulations, and not to rely on absolute bubble growth of a particular simulation.

Table VII is a list of input conditions for the habitat where flammability limits are not exceeded, but there are no constraints to maintain the 1.68 $N_2$/1.0 Ar ratio, at least in the last two entries. Figure 11 shows the bubble growth index (BGI) as a function of an 8-hr EVA for the input conditions in Table VII and the bubble model constants in Table VI.

***Table VII. Simulation Data That Do Not Exceed Flammability Limits But Do Not Constrain the $N_2$ – Ar Ratio in Two Cases***

| Curve | Total Pressure (psia) | $O_2$ (psia, %) | $N_2$ (psia, %) | Ar (psia, %) | Prebreathe (min) |
|---|---|---|---|---|---|
| a | 10.0 | 2.80 (28.0%) | 4.52 (45.2%) | 2.68 (26.8%) | 30 (Option 3) |
| b | 9.0 | 2.70 (30.0%) | 3.95 (43.9%) | 2.34 (26.0%) | 30 (Option 2) |
| c | 8.0 | 2.56 (32.0%) | 3. 41 (42.6%) | 2.02 (25.2 %) | 30 (Option 1) |
| d | 8.0 | 2.56 (32.0%) | 5.44 (68.0%) | 0 | 30 |
| e | 8.0 | 2.56 (32.0%) | 5.44 (68.0%) | 0 | 90 |

BGI equals the ratio of final bubble radius to initial bubble (nuclei) radius. The initial bubble radius is always 3 microns in these simulations. BGI decreases from curve “a” to “e” as less Ar is used (therefore more $N_2$ is used) in the habitat atmosphere, and as prebreathe time is increased from 30 to 90 min (curve “e”). Curve “c” shows a maximum BGI of about 125. Unfortunately, this curve is from the condition that provides for a TR of 1.30 without prebreathing, which was assumed to be safe. This is the type of discrepancy at this stage of the evaluation that prevents me from making a firm statement of DCS risk as a probability, complete with confidence intervals. The BGI for curves “a” and “b” would decrease to about 125, matching curve “c,” if the prebreathe were extended from 30 to 225 min for curve “a” and from 30 to 130 min for curve “b.” It might be that growing bubbles in lipid tissue has nothing to do with Type I “pain only” symptoms, which is mostly what our TR models are about. Bubble growth in lipid tissue may have everything to do with Type II symptoms, but it is difficult to model this category of DCS due to the lack of data. Even curve “e,” which includes 90 min of prebreathe and no Ar in the habitat, is disappointing since BGI is still large and there is still growth (positive slope) at the end of the EVA. At some point, the decision to test promising EVA procedures would be made to validate both the procedures and the predictive models.

Table VIII is a list of input conditions for the habitat where flammability limits are exceeded, but the 1.68 $N_2$/1.0 Ar ratio is maintained. Figure 12 shows the BGI as a function of an 8-hr EVA for the input conditions in Table VIII and the bubble model constants in Table VI.

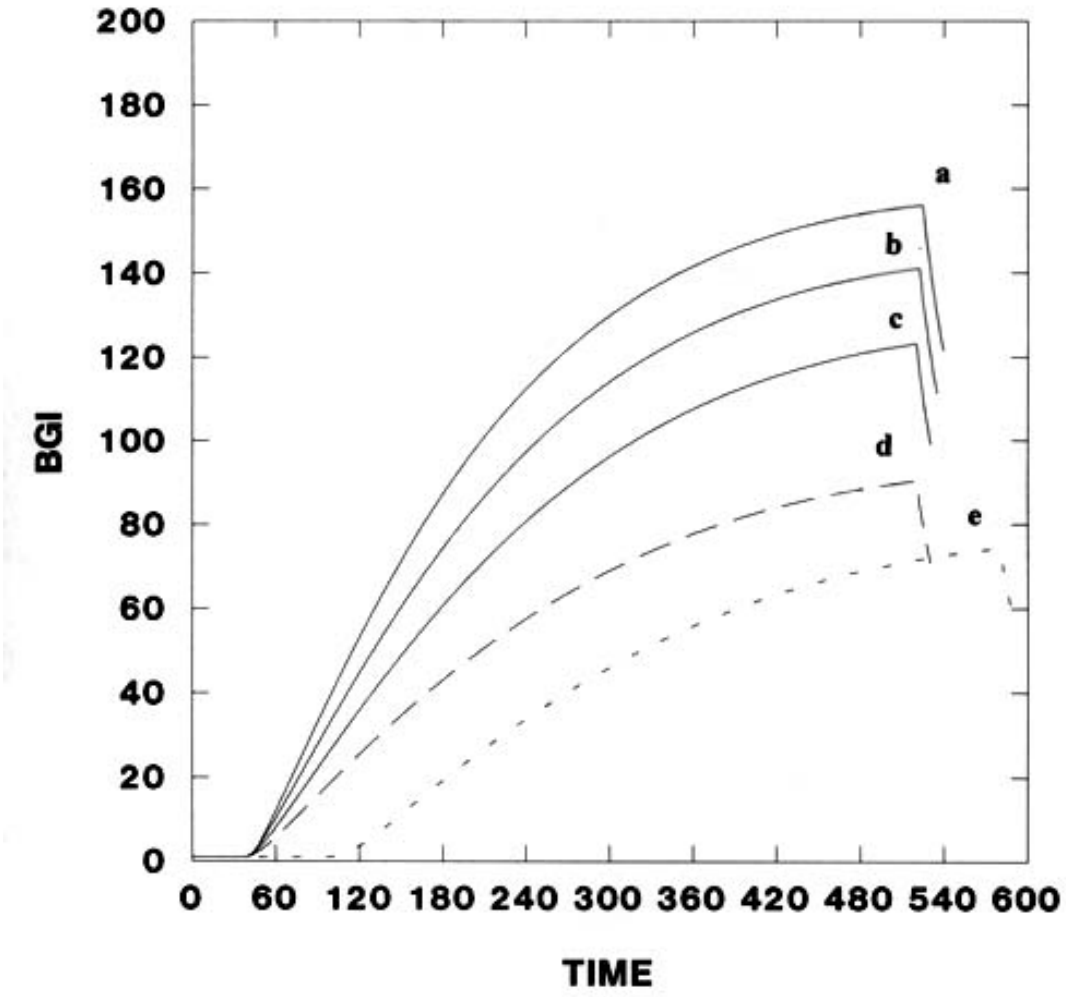



***Figure 11. A bubble grows rapidly and to a large size in lipid tissue with trinary or binary breathing gases in the Mars habitat. The BGI is bubble radius divided by an initial bubble radius of 3 microns. Curves a, b, and c are the results of input conditions for Options 3, 2, and 1. The best result is curve "e," where a gas mixture of 68% $N_2$ – 32% $O_2$ was breathed in an 8.0-psia habitat before a 90-min $O_2$ prebreathe, before an 8-hr EVA at 3.75 psia.***

***Table VIII. Simulation Data That Do Exceed Flammability Limits But Constrain the $N_2$ – Ar Ratio***

| Curve | Total Pressure (psia) | $O_2$ (psia, %) | $N_2$ (psia, %) | Ar (psia, %) | Prebreathe (min) |
|---|---|---|---|---|---|
| a | 10.0 | 5.00 (50.0%) | 3.14 (31.4%) | 1.86 (18.6%) | 30 |
| b | 9.0 | 4.50 (50.0%) | 2.82 (31.4%) | 1.67 (18.6%) | 30 |
| c | 8.0 | 4.00 (50.0%) | 2.51 (31.4%) | 1.49 (18.6%) | 30 |
| d | 8.0 | 3.60 (45.0%) | 2.76 (34.5%) | 1.64 (20.5%) | 30 |
| e | 8.0 | 3.20 (40.0%) | 3.01 (37.6%) | 1.79 (22.4%) | 30 |

It appears that even exceeding the flammability limits for the habitat does not dramatically blunt the contribution of Ar toward bubble growth in lipid tissue. Based on Figs. 11 and 12, the contribution of Ar should be minimized. If there are still bubbles after an 8-hr EVA, they would respond to the recompression and 100% $O_2$ at 11.75 psia, 12.75 psia, or 13.75 psia. These are the maximum pressures that would be available in the suit if the suit were inflated to 3.75 psia above the proposed habitat pressures. It may be a routine procedure to treat with the higher $O_2$ pressure for, say, 30 min, and certainly if bubbles were present during the exposure. The case of repeated EVAs should also be evaluated. Bubble growth and reabsorption during a particular work-rest EVA cycle could be modeled, but the confidence in the results is low due to the complexity of the situation as the time-line is extended into several days.

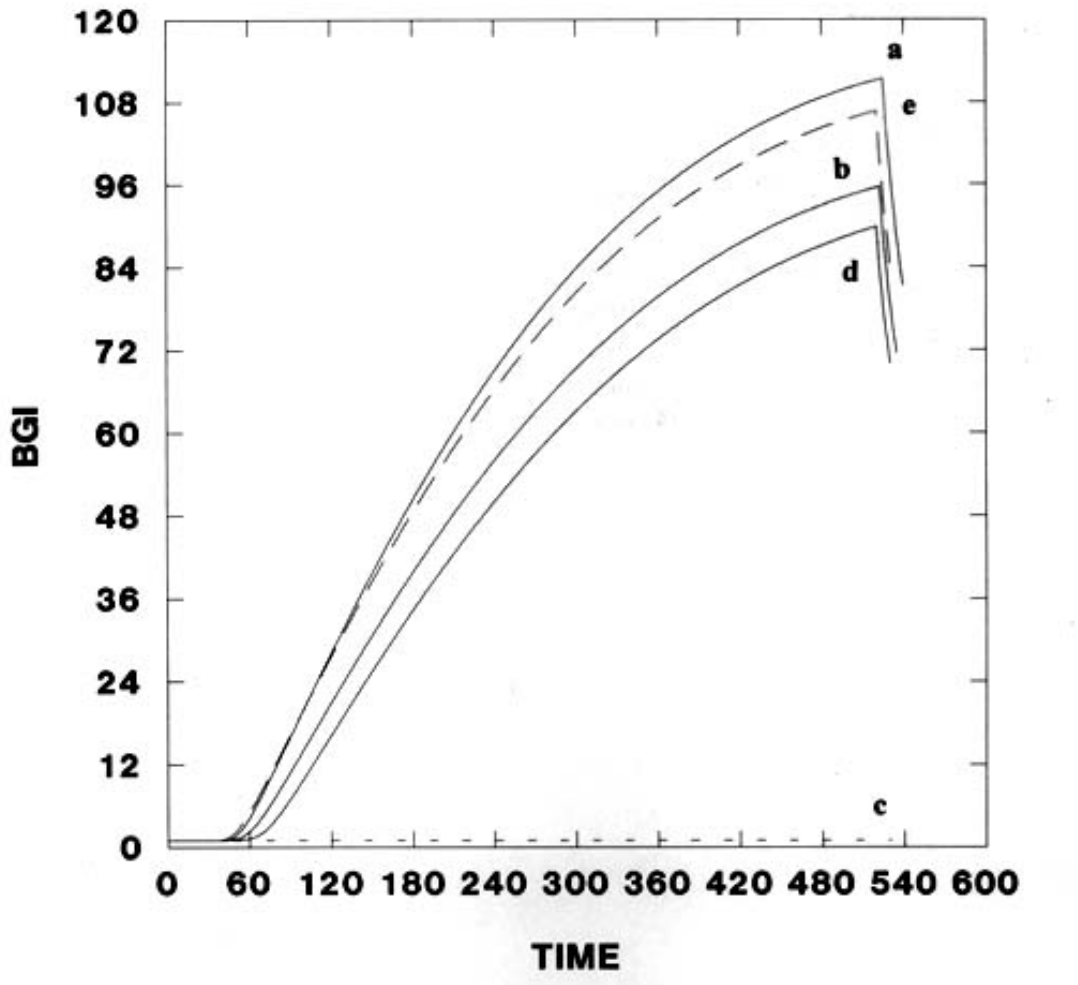



***Figure 12. A bubble grows large, but not as large as some in Fig. 11. Note that the BGI scale has been expanded. The additional $O_2$ in the habitat reduces the Ar and $N_2$ inert gas in the tissue. The best result is curve "c," where 50% $O_2$ with a balance of $N_2$ and Ar at the 1.68 ratio is used in an 8.0-psia habitat. The addition of a 30-min nominal $O_2$ prebreathe before an 8-hr EVA at 3.75 psia aided in preventing bubble growth.***

## Conclusions

This analysis was an initial effort to frame the problems associated with selecting an atmosphere for the Mars habitat with the primary goal to prevent DCS. I made several assumptions along the way. Appendix B lists the assumptions, as well as recommendations. I took the position of evaluating three habitat atmospheres that provide the least cost in terms of money, energy, and engineering to provide. The Mars Program Office would request to evaluate this as their first choice.

An achievable goal associated with human exploration of space and the planets is to prevent DCS (25). This goal is achievable, but the solution is multivariable and always needs to be systematically evaluated. If all consideration were given to the engineers to develop an economical breathing atmosphere, then the Mars habitat would contain a significant concentration of Ar. The solution to unrestricted EVAs would fall to the operation and medical community to provide for lengthy $O_2$ prebreathes to avoid DCS. The lengthy prebreathing could be done in a special room where materials and cleanliness are compatible with a higher concentration of $O_2$. An alternative is to institute a program of exercise during prebreathe to reduce the time to achieve a safe prebreathe, but exercise before a lengthy EVA is not the best operational option. If all consideration were given to the medical community, then the greater technical and higher monetary cost to blend an atmosphere with low Ar concentration and high $O_2$ concentration would be acceptable.

A detailed evaluation of gender differences is needed if Ar is a major component of the habitat atmosphere. The age-old observation that women have more fat as a fraction of total body weight compared to men, and that the fat is distributed more uniformly compared to men undoubtedly has more significance in an atmosphere containing Ar than one containing only $N_2$. Women tend to have fewer bubbles than men detected in the pulmonary artery in tests that involve denitrogenation with 100% $O_2$ after saturation on air (results not yet published). It is not known if they are less likely to form bubbles in the tissues or capillaries, or if the evolved gas just stays trapped in the muscle and fat, or a combination of both.

Finally, this report does not explore the important issue of hyperbaric treatment capability on Mars. The ability to treat DCS with increased pressure and 100% $O_2$ in the Rover vehicle with more aggressive capabilities in the habitat is needed if some risk of DCS is judged acceptable. The results from this evaluation may encourage discussions about acceptable DCS risk with balanced treatment capabilities.

I conclude that this economical approach would drive a risky EVA program in terms of DCS. This conclusion needs to be challenged with empirical data from well-designed human trials. It is not possible to confidently extrapolate from what is currently known about Ar in decompressions of humans or animals to humans on Mars. Ar has no redeeming qualities as a gas to avoid DCS. Dr. Roth (25), the grandfather of U.S. spacecraft atmospheres, summarizes his analysis of inert gases by stating, “Argon, krypton, and xenon can be eliminated quite clearly on the grounds that they increase the hazard of DCS above the level of the $N_2$ hazard.” One

could argue that extra $N_2$ from Earth is needed to dilute Ar in the habitat, that Martian $N_2$ and Ar need to be separated and stored in different containers, or that a separate prebreathe room be provided with a greater range of $O_2$ concentration.

Argon in a 1.68 $N_2$/1.0 Ar ratio could be made to work on Mars, but routine and fast access to the surface would be sacrificed. Lengthy prebreathes in the suit or in a prebreathe room would be needed. A pre-EVA exercise routine during the prebreathe might be advisable (20,31). Doppler bubble monitoring of the pulmonary artery or carotid artery during and after an EVA would be recommended to act as an early warning system to terminate an EVA or to initiate a treatment. Adequate hyperbaric treatment capability would not be an option, and finally, a testing program to validate potential procedures and predictive models for both men and women would be required.

***Extravehicular activity far away from the Mars habitat, and far away from Earth.***

Courtesy of the Mars Society Web Page: www.marssociety.org, October 1999.

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# Appendix A: Computing the $N_2$ to Ar Pressure Ratio

Given a $N_2$ to Ar concentration ratio of 1.68 for the inert gas component of the Martian atmosphere: 2.7% $N_2$/1.6% Ar = 1.68, then the ratio of $N_2$ and Ar pressures in a Mars habitat that also results in a 1.68 ratio of concentrations is:

$N_2$ pressure = Ar pressure $*$ 1.68

Ar pressure = total inert gas pressure (tigp) - $N_2$ pressure

tigp = Ar pressure + $N_2$ pressure

$N_2$ pressure = (tigp - $N_2$ pressure) $*$ 1.68

dividing both sides by $N_2$ pressure

1 = [(tigp - $N_2$ pressure) $*$ 1.68]/$N_2$ pressure

simplify and solve for $N_2$ pressure

1 = [(tigp $*$ 1.68) - (1.68 $*$ $N_2$ pressure)]/$N_2$ pressure

1 = [(tigp $*$ 1.68)/$N_2$ pressure] - 1.68

$N_2$ pressure = (tigp $*$ 1.68)/2.68

# Appendix B: Assumptions and Recommendations

**I assume that:**

- there is no overwhelming imperative or requirement to have an Earth-normal atmosphere in a Mars habitat.
- gas transfer and bubble growth in lipid (even if modeled correctly) provides useful recommendations about DCS and potential embolic risk.
- there are no evolved gas differences between males and females after saturation in a hypobaric environment that contains Ar.
- the low bubble density case is all that needs to be considered for hypobaric DCS.
- a TR of 1.30 on Mars is safe with $N_2$ – Ar – $O_2$ gases at a suit pressure of 3.75 psia.
- Ar has a 720-min half-time.
- $N_2$ has a 360-min half-time.
- all of the inputs to the BGI model are reasonable.
- P(DCS) predictions are reasonable assuming the benefit from saturation in $N_2$ at a lower pressure compensates for the increased DCS risk for the same TR while using a 3.75-psia suit.
- shirtsleeve ambulation in one-g is more stressful than walking on Mars with life support equipment and tools.
- some benefits observed with adynamia in our Earth-based tests will transfer to Mars.

**I recommend that:**

- a 1.68 $N_2$/1.0 Ar ratio in a 8.0, 9.0 , or 10.0 psia Mars habitat could be made to work, but long prebreathe times with 100% $O_2$ must be provided, which delay access to the surface.

- DCS risk on a daily basis is too great with 1.68 $N_2$/1.0 Ar ratio, and provisions to monitor for bubbles (arterial and venous) and treat symptoms with hyperbarics be provided.

- if a 1.68 $N_2$/1.0 Ar ratio is used, then provide a separate prebreathe room where $O_2$ concentration can be increased.

- if a 1.68 $N_2$/1.0 Ar ratio is used, then provide a space suit with variable working pressures that compensates for the DCS risk.

- prebreathe should be considered as protective margin, not as an operational solution to the problem that is fixed at the last minute.

- a minimum operational prebreathe of 30 min be established.

- the Ar component should be diluted by 50%, preferably with $O_2$.

- tests with men and women be conducted to verify candidate procedures since available data or reasonable extrapolation from that data does not provide all the answers.

- a real-time bubble detection system for inside the suit be developed since Ar has a greater embolic potential, even if the Type I DCS risk is acceptable.

- exercise during any prebreathe be done to accelerate inert gas removal.

- a high $O_2$ pressure treatment, say 30 min, in the Rover vehicle or back at the habitat be routine, and certainly if bubbles were detected during the exposure.

- treatment capability of increased pressure and 100% $O_2$ in the Rover vehicle is available in the event that DCS occurs a great distance from the habitat.

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A cost-effective approach for Mars exploration is to use available resources, such as water and atmospheric gases. Nitrogen (N2) and argon (Ar) are available and could form the inert gas component of a habitat atmosphere at 8.0, 9.0, or 10.0 pounds per square inch (psia). The habitat and space suit are designed as an integrated system: a comfortable living environment about 85% of the time and a safe working environment about 15% of the time. A goal is to provide a system that permits unrestricted exploration of Mars, but the risk of decompression sickness (DCS) during the extravehicular activity in a 3.75-psia suit, after exposure to any of the three habitat conditions, may limit unrestricted exploration. I evaluate here the risk of DCS since a significant proportion of a trinary breathing gas in the habitat might contain Ar. I draw on past experience and published information to extrapolate into untested, multivariable conditions to evaluate risk. A rigorous assessment of risk as a probability of DCS for each habitat condition is not yet possible. Based on many assumptions about Ar in hypobaric decompressions, I conclude that the presence of Ar significantly increases the risk of DCS. The risk is significant even with the best habitat option: 2.56 psia oxygen, 3.41 psia N2, and 2.20 psia Ar. Several hours of prebreathing 100% O2, a higher suit pressure, or a combination of other important variables such as limited exposure time on the surface or exercise during prebreathe would be necessary to reduce the risk of DCS to an acceptable level. The acceptable level for DCS risk on Mars has not yet been determined. Mars is a great distance from Earth and therefore from primary medical care. The acceptable risk would necessarily be defined by the capability to treat DCS in the Rover vehicle, in the habitat, or both.

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