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An Evidenced-Based Approach for Estimating Decompression Sickness Risk in Aircraft Operations

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Introduction

Aircraft operations are an integral part of NASA/Johnson Space Center's (JSC) mission as the lead center for manned spaceflight. Pilots from both the Aircraft Operations Directorate and the Astronaut Corps, as well as many other non-pilot aircrew and passengers, are routinely exposed to reduced atmospheric pressure during flights in the T-38 and several different transport aircraft. Flight in pressurized aircraft reduces the potential for developing decompression sickness (DCS) by limiting the change in pressure of the aircraft cabin, but the risk increases in the event of cabin depressurization (3). In this article we present an evidence-based approach for estimating the risk of DCS during normal aircraft operations and during aircraft cabin depressurization.

Information on the incidence of DCS is obtained from three sources: aircraft operations safety data, altitude chamber studies, and mathematical modeling programs. Data from aircraft operations are particularly useful because they represent the actual aircraft, flight profiles, and aviators for whom one is trying to make a DCS risk prediction. An additional advantage is the large number of exposures (flights) which occur in most aircraft operations. Limitations include the lack of information regarding the actual altitude profile flown and the questionable adequacy of DCS diagnosis and reporting (4).

Operational data used to calculate the incidence of DCS are not ideal for several reasons. Most of the altitude excursions are modest (16,000 to 18,000 feet cabin altitude), resulting in a low observed DCS incidence rate. Consequently, determining the true incidence of DCS requires a large number of exposures. In addition, the occurrence rate for significant cabin depressurization is low, reducing the amount of data available outside the normal cabin altitude operating range. One must also be aware of potential selection and reporting biases when interpreting operational data from aviation communities, since medical screening and retention standards might select out some individuals sensitive to DCS.

Altitude chamber studies offer some advantages over the aircraft operations data. The altitude exposures are better controlled and the diagnosis of DCS is more likely to be valid, since experienced examiners are present and the stigma of reporting is minimized. In addition, during many altitude chamber studies, subjects are periodically questioned regarding DCS symptoms. Using altitude chamber data to make operational decisions is, however, subject to the following limitations:

- 1) The altitude chamber exposures are usually more severe, resulting in a greater incidence of DCS.
- 2) The test subject population may not be representative of the typical aviator.
- 3) A relatively small number of subjects and/or altitude exposures are tested during a typical altitude chamber trial.
- 4) Denitrogenation protocols can vary from study to study.
- 5) The conditions in the altitude chamber are not, in general, strictly analogous to the aviation environment. For instance, in many studies subjects are allowed to ambulate at altitude, increasing their risk of developing DCS.

Mathematical models of bubble growth can provide some useful adjunct information (5). They can predict which conditions of pressure, denitrogenation, and time at altitude may promote the growth of the bubble precursors, called micronuclei. These models derive their properties from basic physical principles, and are mathematically rigorous. These models can also be optimized through feedback with actual operational data, assuming that the occurrence of DCS can be defined. The downside to these models is that the pathophysiology of DCS is not completely understood, and modeling the effects of gas bubbles on various bodily systems is difficult or impossible with our current understanding. In addition, it is difficult to correlate clinical symptomatology with bubble size or number.

A second type of model, which provides some of the benefits of both the altitude chamber studies and the mathematical models, are survival models (2). These are essentially meta-analyses of a large number of altitude chamber studies for which a mathematical model has been developed for determining DCS probability (1,2). Disadvantages of this technique include utilization of many different altitude chamber tests, which may mean different criteria were used to diagnose DCS. Also, subtle differences in the conduct of these tests may influence the incidence of DCS, such as a bias to report or not report mild symptoms.

Methods

To illustrate how one can utilize aircraft operations safety data, altitude chamber studies, and mathematical modeling programs in concert, we will examine the case of NASA's T-38 aircraft. The T-38 is a two-seat jet trainer developed by the U.S. Air Force (USAF) in the 1950s. It is used extensively by NASA to maintain flight proficiency for its aircrew and astronauts. The typical flight profile for the NASA T-38 is an ascent to approximately 41,000 feet above mean sea level over a period of 15 minutes, cruise flight at altitude for approximately 1.3 hours, and 10 minutes for descent and landing. The cabin pressurization schedule is ambient pressure until one ascends to 8,000 feet (10.9 psi), maintains the pressure at 8,000 feet equivalent until one ascends to approximately 23,000 feet (5.9 psi), and above that maintains the cabin pressure at a 5-psi differential. NASA flight crew do not routinely prebreathe 100% oxygen and typically fly with the oxygen regulator (CRU-73/A) in the "normal," diluter demand mode. The percent oxygen in the breathing mixture is variable, based upon the normal variability of the oxygen regulator, but is designed to maintain a sea level equivalent oxygen tension in the aviator's blood.

Approximately 600 flights per year are conducted in NASA T-38's. A review of 20 years of aircraft operations safety data reveals approximately one cabin pressure system failure every two years, and no reported occurrences of DCS (Personal communication, NASA/JSC Safety Office, Ellington Field). Assuming 20 years of 600 flights per year and no observed DCS, the probability of DCS is no greater than 0.025% for each flight (95% upper confidence limit as expressed by solving $(1-p)^n = 0.05$ or $p = 1-(0.05)^{1/n}$). An analogous review of USAF T-38 flight operations revealed 294 cases of cabin pressurization system failure for the years 1987 to 1992, at altitudes ranging from 17,000 to 43,000 feet (Personal communication, Headquarters, Air Force Safety Center, Kirtland AFB).

Unfortunately, no data are available on the total number of T-38 flights during those years or on the occurrence of decompression sickness during either normal aircraft operations or inadvertent cabin depressurization.

The survival model, based on 1075 exposures in 66 chamber flights, predicts a DCS probability of <1% for routine cabin altitudes (Figure 1). The probability isopleths are calculated from four variables:

- the exposure altitude
- the time at the exposure altitude
- the amount of denitrogenation (the effective 100% oxygen prebreathe time)
- the presence or absence of repetitive physical activity.

It is assumed that T-38 pilots are not active (not exercising) during normal flying activities. Since the inspired oxygen concentration varies with cabin pressure, the amount of denitrogenation occurring in flight cannot be accurately determined, thus the following assumption was made: For flight times from 10 to 90 minutes, in intervals of 10 minutes, the effective 100% oxygen prebreathe time is four minutes per interval (e.g. 4 min., 8 min., etc.). Flights to 10,000 feet or less had no effective prebreathe time.

Results

After reviewing the operational data and survival model predictions, we must undertake the challenge of estimating a safe upper limit for cabin altitude during normal aircraft operations. Case reports of DCS have occurred at altitudes as low as 8,000 feet (9), but DCS is unlikely in typical aircraft operations until one reaches altitudes above 20,000 feet (6). Above this, however, the risk of DCS increases and is heavily dependent upon altitude, time at altitude, physical activity at altitude, and duration of denitrogenation. The cabin altitude upper limit could thus be set with confidence in the normal operating range, for instance at 18,000 feet since flights do not usually exceed 41,000 feet, but then normal aircraft operations would violate this altitude restriction. With an excellent safety record, and a predicted DCS incidence rate of 0.025%, the evidence does not support this limitation.

Based upon NASA's experience with T-38 aircraft over the past 20 years, on the predictions of the survival model, and in conjunction with data from the USAF T-38 flight program, our recommendation is that NASA T-38 cabin altitude be limited to 25,000 feet. This results in a calculated DCS probability of less than 5% for one hour or less at 25,000 feet, based on the

survival model. No predictions regarding OCS probability can be made for this profile using the T-38 operational data since it lies outside the aircraft's normal cabin altitude operating range and since neither NASA nor the USAF has adequate data on DCS occurrence during cabin pressurization system failure. It should be noted, however, that the probability for developing DCS could be above 30% for even relatively brief exposures to altitudes above 40,000 feet, based on the survival model (Figure 2) and other altitude chamber experience.

Since repeated exposure to altitude over short-time intervals has been shown to increase the risk of developing DCS (7), we recommend that any crew member exposed to altitudes in excess of 25,000 feet not be assigned to flying duties for 12 hours after the occurrence. These individuals may fly as passengers on aircraft in which they do not have access to flight controls or critical flight-related tasks, providing the aircraft cabin altitude does not exceed 10,000 feet. These individuals should be made aware that they are at risk for developing DCS even if the aircraft cabin remains at or below 10,000 feet (10). These individuals should also be aware that they are at significantly increased risk of developing DCS should the cabin pressurization system fail on the subsequent flight.

Discussion

It must be made clear that this 25,000-foot aircraft cabin altitude limit is specific to NASA's T-38 aircraft and takes into account the following five facts:

- 1) NASA pilots do not spend a significant amount of time denitrogenating.
- 2) Flight operations are typically conducted with the oxygen regulator in the "normal," diluter demand mode.
- 3) T-38 crew members are not able to ambulate or exercise significantly at altitude.
- 4) The time the aircraft can spend at altitude is limited to approximately 1.3 hours during routine flight due to fuel constraints.
- 5) The population for whom these predictions are made has extensive high-altitude aviation experience and is not necessarily representative of other aviator populations.

We believe that the incidence rate of DCS for our aircrew using this protocol will be no worse than 5%, and will in all likelihood be considerably lower. In order to further decrease the likelihood that one of our pilots might experience an episode of DCS, we are recommending that the cabin altitude be maintained at or below 18,000 feet if possible for all flights. Additional safeguards, such as flying with the oxygen regulator set to 100%, have been suggested (11).

In conclusion, we discussed a strategy for combining all available information regarding the predicted incidence of DCS for a specific type of aircraft and the development of a systematic, evidence-based approach for setting limits on the acceptable decompression profiles for an aircrew population. It is important to note, however, that the individual aviator continues to accept the small but non-zero risk of DCS incurred during each flight. It is only through feedback from these aviators and the flight surgeons who provide care for them that more complete data on DCS occurrence during cabin pressurization system failure can be documented, and improvements in aircrew safety can continue to be made.

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Approximate T-38 Flight Envelope Worst Case and Nominal

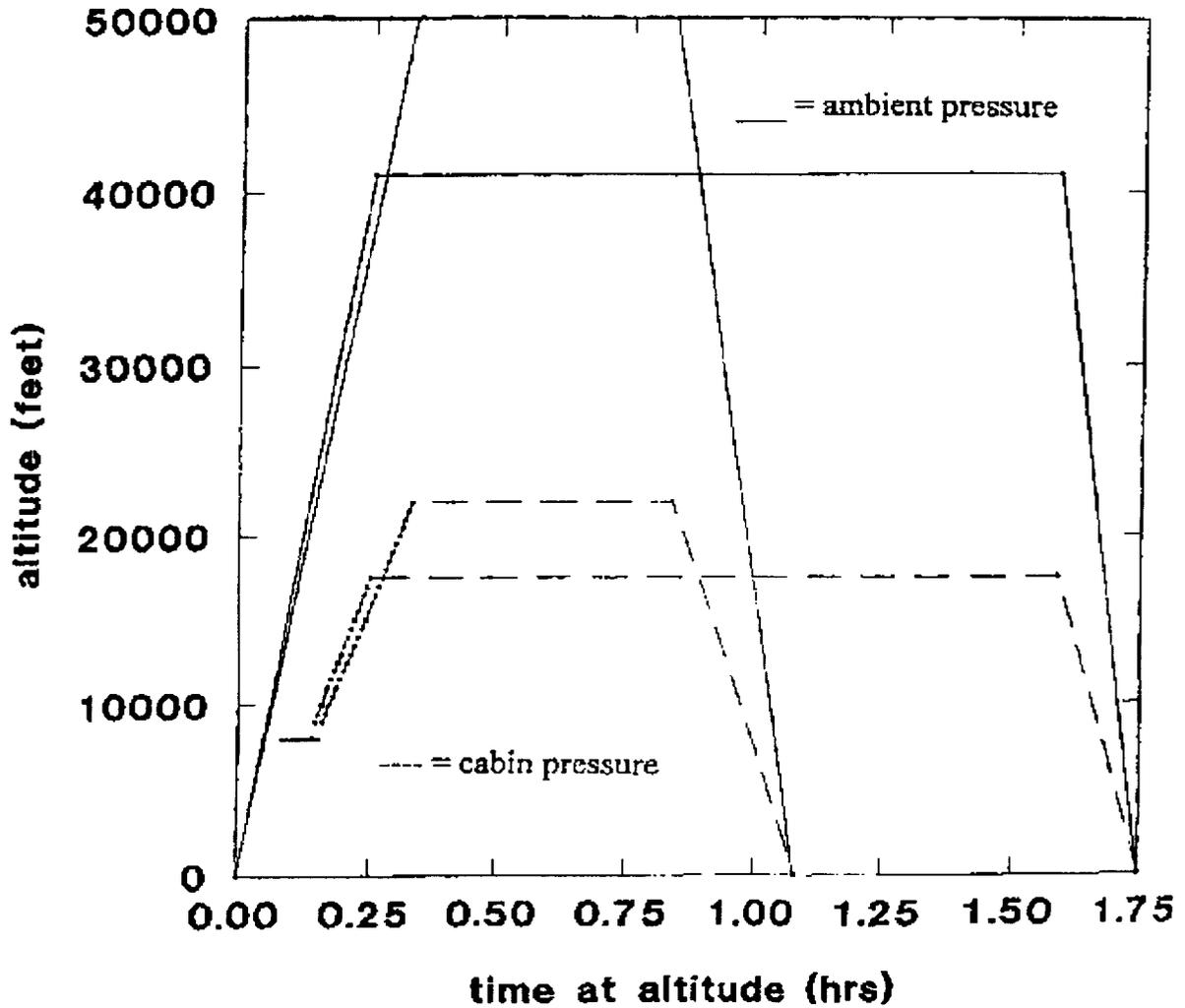


Figure 1. The T-38 flight envelope for the worst and nominal cases. The two solid lines represent the flight envelope for ambient pressure (as altitude) and the dashed lines represent cabin pressure (as altitude). The T-38 flight time is limited to about 1.75 hours.

DCS probability space where EXERCISE = 0 (best case)

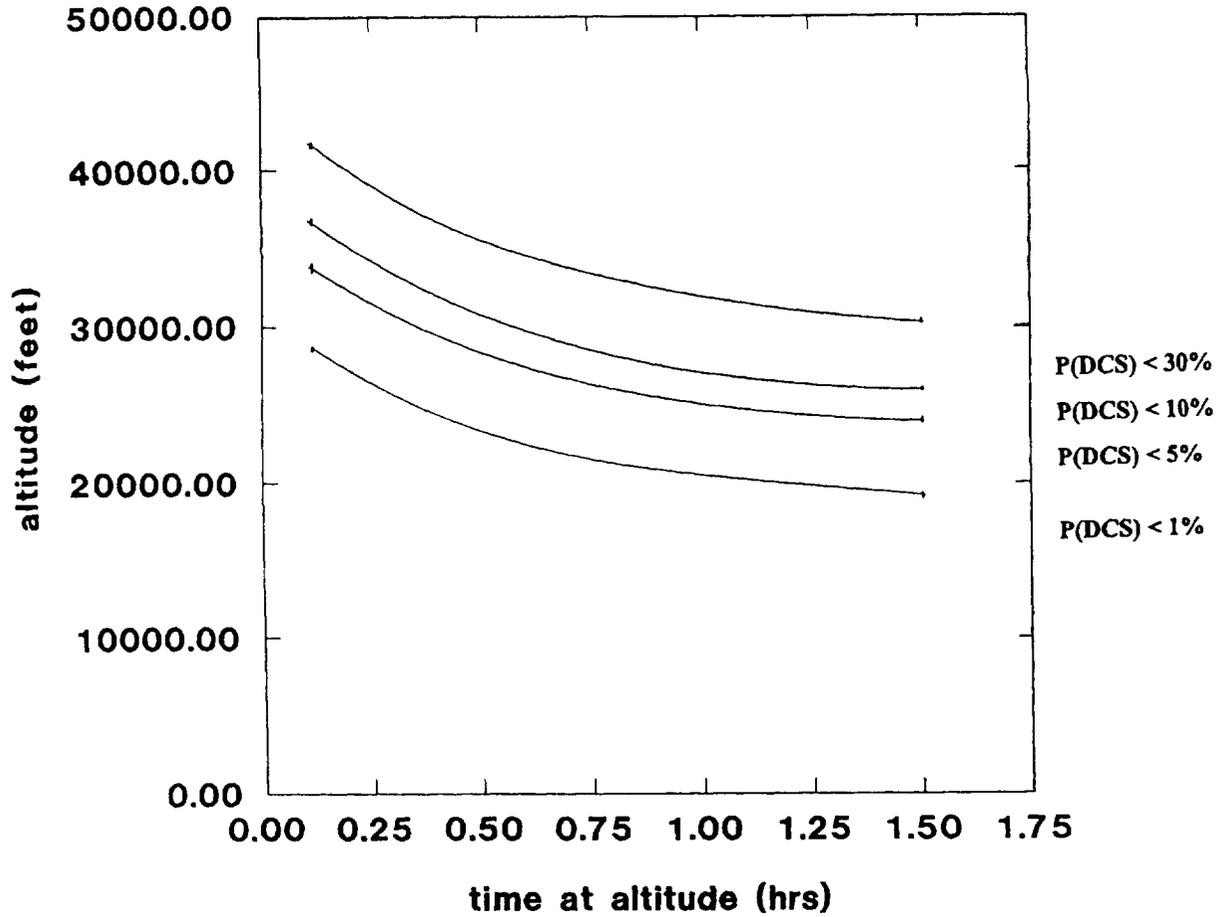


Figure 2. Decompression sickness (DCS) probability isopleths given that the crew are inactive during the flight. For example, exposure to 20,000 feet for 1.25 hours in an inactive crew puts the risk of DCS at less than 1%.

DCS probability space where EXERCISE = 1 (worst case)

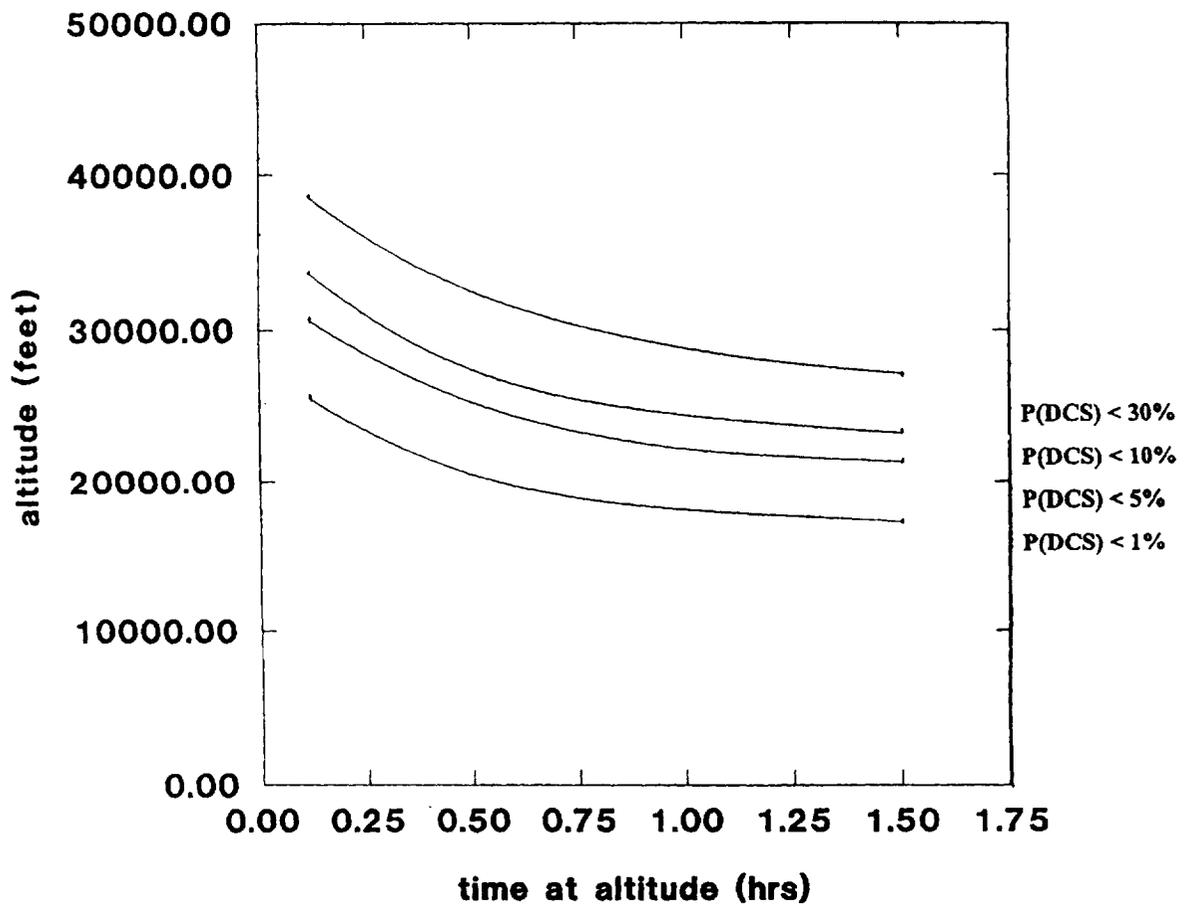


Figure 3. Decompression sickness probability isopleths given that the crew are physically active during the flight. For example, exposure to 20,000 feet for 0.50 hours in an active crew puts the risk of DCS at less than 1%.

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