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Concepts Providing for Physiological Protection After Aircraft Cabin Decompression in The Altitude Range of 60,000 to 80,000 Feet above Sea Level

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16. Abstract

The European aircraft Concorde provides evidence that the technology required for building supersonic passenger transport has long been available. In the United States, development efforts for this type of airplane were functionally abandoned in the early 1970s. In recent years, changes in technology, world political structures, and economics have stimulated interest in the development of a fleet of supersonic transports for use in civilian aviation. The future aircraft has been designated the High Speed Civil Transport (HSCT). As part of the development process, all potential challenges associated with design characteristics of the aircraft must be addressed. This report reviews the physiological issues related to cabin decompression during high-altitude flight. A number of strategies for protecting passengers and crewmembers after high-altitude cabin decompression are discussed. Due to the physiological consequences associated with high-altitude decompression, a combination of protective systems may be necessary. At a minimum, it would appear that increased structural integrity of the cabin, a repressurization system, and an optimally designed supplemental oxygen system for crew and passengers are required.

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CONCEPTS PROVIDING FOR PHYSIOLOGICAL PROTECTION AFTER AIRCRAFT CABIN DECOMPRESSION IN THE ALTITUDE RANGE OF 60,000 TO 80,000 FEET ABOVE SEA LEVEL

1.0 INTRODUCTION

When public air transportation first became commonly available, flight altitudes did not reach altitudes that represented a significant risk of hypoxia or decompression sickness to either passenger or crew. Both passengers and airlines soon recognized the economic benefits of faster, higher flying aircraft. During the 1950s and 1960s aircraft were developed and refined that allowed consistent, safe transport of the flying public at altitudes around 40,000 feet. Some of the more popular transport category aircraft models and certification altitudes are presented in Table 1.

As can be seen in this table, operational altitudes have remained relatively consistent over the last 40 years. Today, significant incentive exists for the development of transport category aircraft whose operational characteristics extend to supersonic speeds and altitudes well beyond 42,000 feet. Currently, leaders within the commercial aircraft industry in the United States have been working with National Aeronautics and Space Administration (NASA) to develop a design approach for a supersonic passenger airplane. This aircraft has been designated the High Speed Civil Transport (HSCT). It is anticipated that current and developing technologies will allow widespread distribution and use of the HSCT to meet the global travel demands of the 21^{st} century. In fact, many specific design characteristics (such as size, speed, and range) have already been identified. To date, numerous reports have reviewed operational issues related to this type of aircraft, including certification (1, 2, 22) and decompression (5, 6, 23). The purpose of this report is to identify technologies that may have the potential to remedy, or at least minimize, the hazards facing passengers and crew of high-speed civilian transports (HSCT) and to identify some limits on aircraft operation to ensure passenger recovery in the event of a cabin decompression.

2.0 BASIC COMPOSITION OF THE ATMOSPHERE

The atmosphere is made up of a variety of gases (Table 2). For reference purposes, atmospheric pressures are referenced to the sea level value of 760 mmHg. In 1801, the English astronomer and chemist, John Dalton, discovered the pressure relationship among gases in a mixture. Dalton's Law states that the pressure exerted by a mixture of gases is equal to the sum of the pressures that each would exert if it alone occupied the space filled by the mixture. It follows from this relationship that the pressure of any

McDonnell Douglas	DC-8-11	August 31, 1959	42,000
Boeing	747-100	December 30, 1969	45,100
Lockheed	L-1011-385-1	April 14, 1972	42,000
Airbus	A300 B2-1A	May 30, 1974	40,000
Lockheed	L1011-3	April 13, 1979	43,000
Boeing	767-300	September 22, 1986	43,100
Airbus	A310-300	June 10, 1987	41,000
McDonnell Douglas	MD-90-30	November 4, 1994	37,000

Table 1. A sample of aircraft used for commercial passenger transport in recent years. The average FAA-approved operational altitude for the aircraft listed above is 41,650 feet.

[illegible]	Molecular Weight (g/mol)	Percent (%) Present in the Atmosphere	Partial Pressure at Sea Level
Nitrogen	28.01	78.08	593
Oxygen	32.00	20.95	159
Argon	39.95	0.93	7
Carbon Dioxide	44.01	0.03	0

Table 2. Primary component gases making up the earth's atmosphere.

gas in a mixture, i.e. its partial pressure, may be calculated by multiplying the total gas pressure by the fraction of the gas in the mixture (Table 2). As altitude increases above sea level the partial pressure of component gases decreases consistent with the decrease in total atmospheric pressure. The partial pressures of gases are critical to physiological functions because pressure differences are responsible for providing the gradients for diffusion of the gases into and out of the body.

2.1 Oxygen

Human beings depend on oxygen (O_2) for cellular respiration. Therefore, adequate supplies of oxygen must be available in habitable environments. The partial pressure of oxygen in the lung at the level of the alveoli (P_AO_2) is roughly 100 mmHg, and the partial pressure of oxygen in the mixed venous blood (P_VO_2) returning to the right atrium is roughly 40 mmHg. As the partial pressure of oxygen in the atmosphere ($P_{atm}O_2$) decreases with increasing altitude, the pressure gradient for diffusion of oxygen into the body is reduced. During acute exposure to altitudes below 15,000 feet, cardiovascular and respiratory compensatory mechanisms act to maintain oxygenation levels at the cellular level. However, these systems cannot preserve arterial oxygen partial pressure (PaO_2) and the corresponding blood oxygen saturation (SaO_2) levels at their sea level equivalents above 15,000 feet. Thereafter, the P_AO_2 of the lung drops as atmospheric pressure decreases at altitude unless supplemental oxygen is supplied.

2.2 Nitrogen and Argon

Atmospheric gases nitrogen and argon are inert in regard to cellular metabolism. Nitrogen plays a significant role in the development of decompression sickness (DCS) resulting from altitude exposure. However, DCS is not considered a potential problem under the operating conditions addressed in this paper and will not be considered further.

2.3 Carbon Dioxide

Carbon dioxide (CO_2) is a by-product of human cellular metabolism. It is expelled from the body during exhalation. Starting at concentrations of about 1%, CO_2 results in a number of deleterious physiological effects. Therefore, it must be removed from any artificial environment designated for normal human activities. Current Federal Aviation Administration regulations permit 0.50% CO_2 in the cabin aboard transport category aircraft.

2.4 The Partial Pressure of Water

Some level of water vapor is usually present in air. The water vapor pressure (PH_2O) of a given volume of air is temperature dependent. Consistent with other atmospheric gases, the PH_2O of air decreases with ascent to altitude. The air in the lungs is consistently saturated with a water vapor pressure of 47 mmHg at the representative body temperature of 37°C.

2.5 Temperature

Temperature decreases with ascent to altitude up to 37K, where it levels off at about -57°C. As mentioned earlier, a representative human body temperature is 37°C. It is accepted that air carrier passenger cabins are maintained at a relatively comfortable temperature range of 20 to 25°C.

3.0 PROBLEMS ASSOCIATED WITH HIGH ALTITUDE FLIGHT

3.1 Brief Overview of Physiological Limitations

The effects of altitude exposure on human physiological processes have been extensively studied and are thoroughly reviewed elsewhere (4, 9). Suffice it to say here that humans depend primarily on oxygen for the energy production necessary to maintain life processes. Reduction in oxygen availability beyond altitudes relatively close to sea level results in significant loss of function ranging from slight impairment to death. Significant human performance decrements resulting from hypoxia begin in the altitude range of 10,000 to 14,000 feet. Beyond these levels, time available before incapacitation is negatively correlated with altitude. Time of Useful Consciousness[1] (TUC) and Time of Safe Unconsciousness[2] (TSU) are indices commonly used to evaluate human responses to decompression. TUC is most appropriately used to characterize the time available for the flight crew to perform an operational task (11). The concept of TSU was suggested specifically to address passenger risk after decompression. Although both physical and physiological factors influencing TSU have been identified (11) it has not been possible to associate a specific time frame with the TSU concept. Currently, 14 CFR Part 25 does not permit passengers to be exposed to altitudes above 40,000 feet and does not allow exposures above 25,000 feet for more than two minutes after a decompression. While some debate may exist in government, academia and industry as to whether or not this rule represents a rational safety standard in the context of current and future passenger aircraft, it currently forms the framework for FAA Regulation. Due to the significance that this issue has for aviation (i.e., passenger and crew) safety, it is recommended that TUC and TSU be addressed by a joint FAA, NASA, other government agencies, academia, and industry evaluation to determine an appropriate standard.

Regardless of what is currently considered to be acceptable altitude exposure limits, it is clear that the altitude range at which the problems of exposure start do not begin to approach the operational limits of current or future aircraft. Therefore, loss of cabin pressurization represents a hazard for the occupants of any modern transport category aircraft. The danger level is significantly increased by decompression at the extreme altitudes of 60,000 to 80,000 feet.

3.2 The Failure Event: Decompression Times and Cabin Altitude Profiles

Decompression events are categorized as explosive, rapid, and slow. An explosive decompression is defined as a complete loss of cabin pressure in one to three seconds. Rapid decompressions take 30 to 60 seconds for the pressure loss to occur. Slow decompression pressure losses are defined in terms of minutes. Cabin decompression can result from a number of events ranging from pressurization system malfunction to penetration of the cabin by a foreign object. Broadly speaking, the biological effects of decompression are dependent upon the following factors (10):

(a) The altitude at which the decompression takes place.
(b) The pressure differential at the time of the failure.
(c) The volume of the pressurized compartment.
(d) The size of the hole permitting loss of pressure.

In addition to being the primary factors influencing the biological effects, these factors also interact to dictate the time of the decompression. Higher flight altitudes are consistent with higher cabin pressure differentials in civilian transports. Large pressure differentials take longer to equalize for a given pressurization failure. Large cabin volumes also slow the rate of pressure equalization, thus increasing decompression times. Decompression times are inversely

[1] Time of useful consciousness is defined as the period of time that elapses between exposure to a reduced oxygen tension in the inspired air and the point when performance becomes so impaired that successful deliberate action becomes impossible (14).

[2] Time of safe unconsciousness is defined as the period of time that a person may be rendered unconscious from oxygen deficiency without production of permanent neurological damage or other health problems.

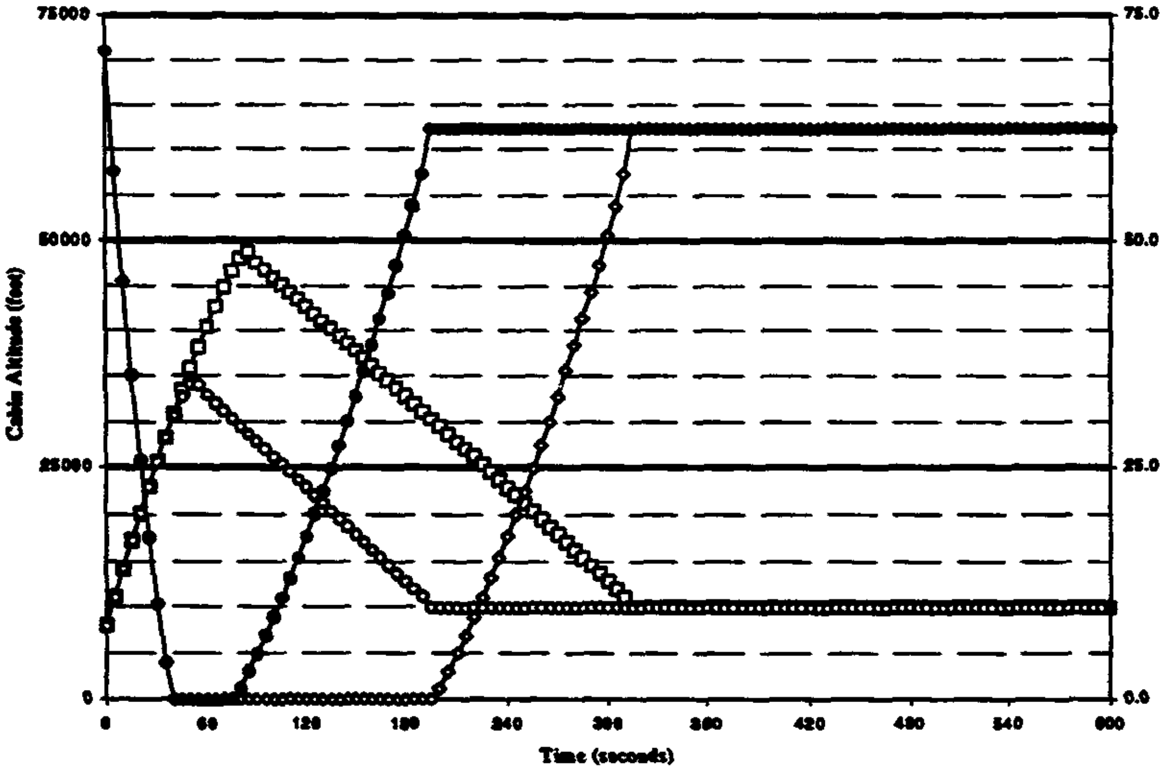

Figure 1. Changes in cabin altitude and lung PO_2 resulting from decompression. The open circles and squares represent changes in cabin altitude resulting from decompression of the cabin from 42,500 and 62,500 feet, respectively. The closed circles and open diamonds represent the corresponding changes in lung PO_2. The initial cabin altitude is 8,000 feet and the emergency descent rate is 10,000 feet / minute for both cases.

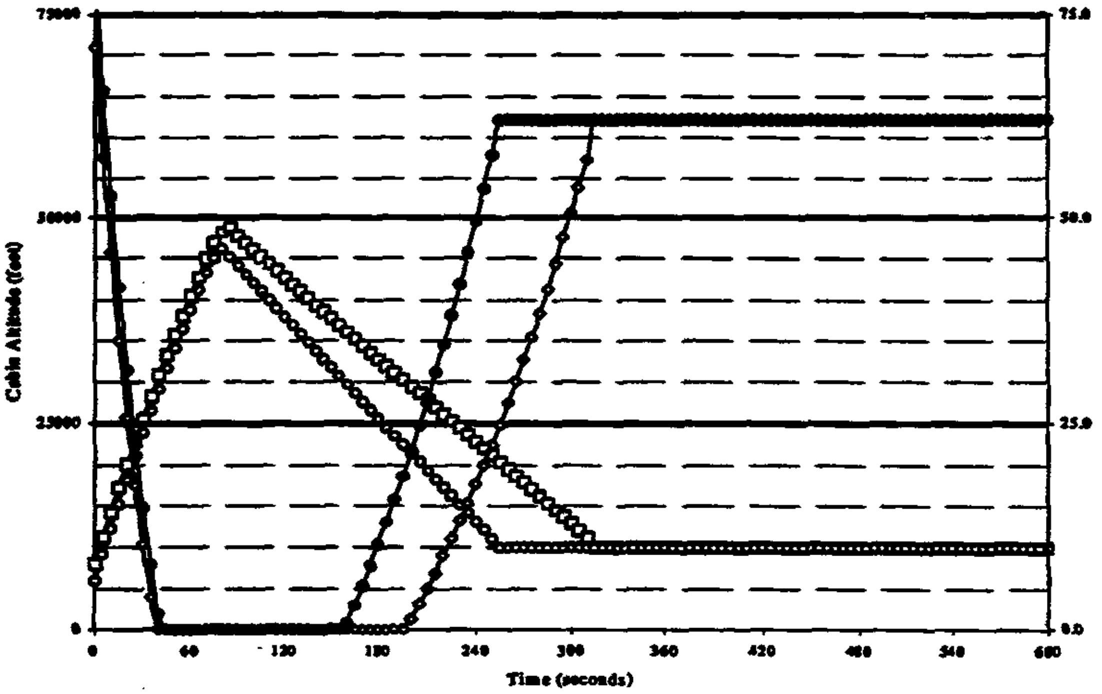

Figure 2. Changes in cabin altitude profiles as a result of lowering the initial cabin altitude and increasing the emergency descent rate. The open and filled circles should be conpared/contrasted with squares and diamonds, respectively.

correlated with the size of the compromise in the aircraft pressurization system or structure. Interaction of the influence of these and other variables on cabin altitude after decompression are presented in Figures 1 and 2. In general, the shorter the time of decompression, the more severe the biological effects.

The rate and pressure range of the decompression determines the magnitude of the effects arising from trapped gases in the body. The maximum cabin altitude and the rate at which it was obtained determine the magnitude of the hypoxic effects. Since the magnitude of the decompression time is negatively correlated with the decompression severity, factors affecting the decompression time have been extensively studied. Most modern presentations (10, 19, 25) and analysis regarding the calculation of aircraft decompression times can be traced to the work of Haber and Clamann (12) and Violette (26). This work is important in that it allows the rate of decompression to be calculated for a given hypothetical pressurization failure. One goal of occupant protection is to reduce the physiological effects of altitude exposure if decompression occurs. Successful investigation in these areas can result in a HSCT design that will extend the time required for any decompression, short of disintegration, thus allowing more time for appropriate emergency responses to be successfully completed, and greater protection for aircraft occupants. NASA High Speed Research resources should be used to support research in the areas of (a) physiological response of passengers and crew to rapid decompression at altitudes typical of a HSCT at cruise, and (b) advanced cabin materials to ascertain responses to internal and external loads associated with a HSCT.

During decompression of a large passenger aircraft, the cabin altitude does not normally reach the flight altitude of the aircraft. Pilots are trained to initiate an emergency descent in response to rapid cabin decompression. The rapid descent attenuates the rate of fall of cabin pressure and the minimum cabin pressure reached as a result of the decompression. This relationship between flight altitude, cabin altitude and time is referred to as the cabin altitude profile. Cabin altitude profiles reflect a complex relationship among the initial flight altitude, the magnitude of pressure loss, the aircraft's descent rate, and cabin volume, initial altitude, and temperature. Again, mathematical analysis of these parameters provides insight into approaches that can be used to minimize occupant exposure to altitude.

Examples of decompressions from altitudes of 42,500 feet and 62,500 feet are presented in Figures 1 and 2. The cabin altitude curves were calculated using a model developed by NASA for theoretical decompression. Although the model parameters do not fit any one specific type of aircraft, the curves do represent the concepts associated with cabin pressure changes after decompression. Estimated values for the partial pressure of oxygen (PO_2) in the lung are calculated from the cabin altitude atmospheric pressure. The responses are calculated using a cabin volume of 25,000 ft^3 and a hole in the structure of 0.9 ft^2. Decompression at a flight altitude of 42,500 feet under these conditions leads to a maximum cabin altitude of approximately 34,000 feet. The cabin altitude exceeds 25,000 feet for 1 minute and 15 seconds. In comparison, decompression at a flight altitude of 62,500 feet results in the cabin altitude reaching nearly 49,000 feet and remaining above 25,000 feet for 3 minutes and 45 seconds.

The graphs use lung PO_2 as an index of survivability for the passenger. Without taking any compensatory changes associated with altitude exposure into account, SaO_2 of 45-50% are associated with PO_2 of 20-25 mmHg. Exposures of 10 to 15 minutes in duration above this level of hypoxia should be survivable for the majority of passengers. The critical concern is the amount of time that can be spent at altitudes where the lung PO_2 is below 20-25 mmHg. Recent investigations related to the immediate cessation of cardiorespiratory function suggests that permanent damage begins at approximately 3 minutes (20, 24). Since immediate and complete failure of physiological function is not anticipated, an exposure limit of 4 minutes at a lung PO_2 less than 22.5 mmHg may be most appropriate. In this context, the lung PO_2 resulting from the theoretical decompression at 62,500 feet borders on producing permanent damage with lung PO_2 reduced below 22.5 mmHg for 3 minutes and 50 seconds. One minute and 50 seconds is the low PO_2 exposure time resulting from a decompression at 42,500 feet.

From the previous discussion, it is obvious that cabin decompression at altitudes in the 60,000 to 80,000 feet range is extremely hazardous. Examples of adjustments that can be made to attenuate the effects of such decompressions are presented in Figure 2. Both sets of data represent decompressions from a flight altitude of 62,500 feet. In one case, the initial cabin altitude is lowered from 8,000 to 6,000 feet, and the emergency descent rate is increased from 10,000 to 12,500 feet / minute. These changes lower the maximum cabin altitude reached by roughly 3,000 feet and reduce the amount of time spent above 25,000 feet, and at a lung PO_2 below 22.5 mmHg, by 1 minute and 20 seconds and 55 seconds, respectively. Although still not consistent with current regulations, the approach is representative of the types of adjustments that can be made to diminish the effects of high altitude decompression.

3.3 Basic Approach to Aircraft Occupant Protection

Current transport category aircraft use redundant systems to protect the passengers and crew from the effects of altitude. The primary protection for aircraft occupants is cabin pressurization. The backup, or emergency, system consists of a supplemental oxygen supply and delivery system for both the crew and the passengers. Aircraft oxygen systems are primarily designed for use in the event of a loss of cabin pressure. The efficacies of these systems are specific to the designated user. Crew systems provide a higher level of physiological protection than do passenger systems.

4.0 BASIC ASSUMPTIONS REGARDING OCCUPANT PROTECTION

4.1 The Flying Population

Civilian air transport has changed over the last 50 years in terms of cost, the number and types of routes flown, the population carried, and the acceptable level of risk associated with flying. No definitive statistical data are available concerning the health of the average transport aircraft occupant. In fact, it is not the medical status of the average occupant that is most relevant. Of primary concern, as far as acceptable limits of physiological protection are concerned, are the individuals who may not have cardiovascular or respiratory deficiencies. The vast majority of data that have been collected on physiological protection from altitude exposure has been gained from investigations using young adult males. Although the information gained in these studies has been very important in the understanding of human physiology at altitude, this group is certainly not representative of the general population.

To date, civilian carriers have not refused to transport any passenger unless extreme medical circumstances demanded consideration. It is difficult to imagine a commercially viable transport aircraft that required a passenger to have a health certificate for boarding. Currently, government regulations require that commercial transport aircraft cabins do not exceed an altitude of 8,000 feet during normal flight operations. It has been suggested that the maximum cabin altitude should be lowered to 6,000 feet (8). This reflects a concern for those individuals suffering from cardiorespiratory problems and the potential detrimental effects of hypoxia on some individuals at cabin altitudes as low as 8,000 feet. Regardless of the cabin altitude that is required, it has been established that the aircraft manufacturer, and subsequent carrier, have an obligation to provide means of passenger protection against high altitude exposure for the vast majority of potential travelers.

4.2 Aircraft Characteristics

An underlying premise of this report is that cabin pressurization will remain the best way to protect aircraft occupants from the extremes of high altitude. At present, cabin pressurization remains the most convenient means of offering the altitude protection desired. Even for the implementation of a first generation domestic high-speed civilian transport category aircraft, the concept of passive occupant protection is very appealing. This approach does not require extensive additional training or inconvenience for the crew and passengers. Another advantage is that aircraft manufacturers have extensive experience in implementing pressurization systems consistent with those used on current transport designs.

The majority of subsonic transport aircraft compress air drawn from the environment to pressurize the cabin. Basically, the desired cabin pressure is maintained by controlling the flow of air through the cabin. A pressurization system on a commercial transport aircraft consists of multiple compressors, redundant pressure controller(s), and a system of valves to maintain the cabin pressure at the desired level. Pressurization schedules are described in terms of isobaric, differential, and isobaric-differential control schemes (19). Normally, each of these approaches is used over the operational altitude range of a given aircraft. The difference in pressure created between the environment and within the cabin is defined as the cabin differential pressure. The limit for the maximum cabin pressure differential that can be achieved is a function of the structural characteristics of the aircraft.

Present cabin pressurization systems aboard subsonic aircraft can maintain pressure differentials in the range of 8.0 to 9.5 pounds per square inch (psi). For example, an aircraft flying at 40,000 feet and maintaining a cabin altitude of 7,500 feet would have cabin pressure differential of 8.4 psi. Increasing the flight altitude to 70,000 feet results in a cabin pressure differential of 10.5 psi. Herein lies a problem. Aircraft structures and pressurization systems currently in use are not designed to consistently operate at cabin pressure differentials this high. The supersonic transport, Concorde, was designed to tolerate high cabin pressure differentials. However, it has not been manufactured in numbers anticipated for the HSCT of the future.

Aircraft design and equipment must be evaluated in terms of both occupant safety and cost. The structural design of current or future aircraft must undergo strict cost/benefit analysis. The analysis must include materials, construction, operation, and maintenance of the aircraft. Ultimately, the decisions regarding the feasibility of any of the approaches presented below would have to be evaluated by aircraft manufacturers and commercial airlines in the context of applicable regulations. In considering physiological protection for the passengers and crew of future high-speed civil transports, alternative systems, other than requiring occupants to wear full pressure suits and helmets, need to be examined. The following discussion is an attempt to present potential solutions that conceptually address the problems of human physiological protection during flights to extreme altitudes.

5.0 PROTECTIVE STRATEGIES

5.1 General Aircraft Design

Regardless of the protective systems utilized, the primary goal is to minimize the risk of decompression to nonexistent levels. An example of this approach is the window size used in aircraft. Windows have long been identified as a potential weak point in aircraft structure (17). Therefore, relatively small windows have been installed in passenger transports. The complete removal of windows from HSCT has been suggested as a means of keeping the risk of decompression at an absolute minimum. Artificial vision systems have been suggested for use by both passengers and crew. There is debate as to whether or not this approach represents an acceptable solution for improving structural integrity. Another approach for reducing the negative aspects of cabin decompression would be to increase flight speeds at lower altitudes. Specifically, design the aircraft so that it can fly at speeds well in excess of the speed of sound at altitudes in the range of 45,000 to 50,000 feet. This would allow a more conventional emergency oxygen system to be used and allow the aircraft to descend to a lower and safer altitude in a shorter period of time. Unfortunately, this does not appear to be a realistic approach, based on functional aerodynamic and structural design limitations or environmental concerns. Therefore, providing a means of protecting occupants from decompression at high altitude must be addressed.

5.1.1 Sealed Cabin

The concept of designing an aircraft routinely capable of extreme flight altitudes is not new. In depth analysis of factors that must be addressed to allow development and implementation of high altitude aircraft were conducted in the 1950s (7). The goal of the analysis was to investigate systems and analyze performance characteristics for use in flight operations between altitudes of 70,000 and 100,000 feet. A solution offered in the report was a perfectly sealed cabin. Using this approach, a cabin construction capable of withstanding the pressure differential of extreme altitudes would be implemented. It is assumed that the structural integrity of such a cabin would be at a lower risk of a decompression event occurring than a conventional transport aircraft using differential pressure systems. However, a sealed cabin brings about a new set of problems. Means of producing a comfortable, safe, breathable atmosphere while eliminating waste products and other unpleasant entities produced within the closed environment would have to be developed. Such a system may impose an excessive penalty in weight, space, and complexity upon the aircraft design.

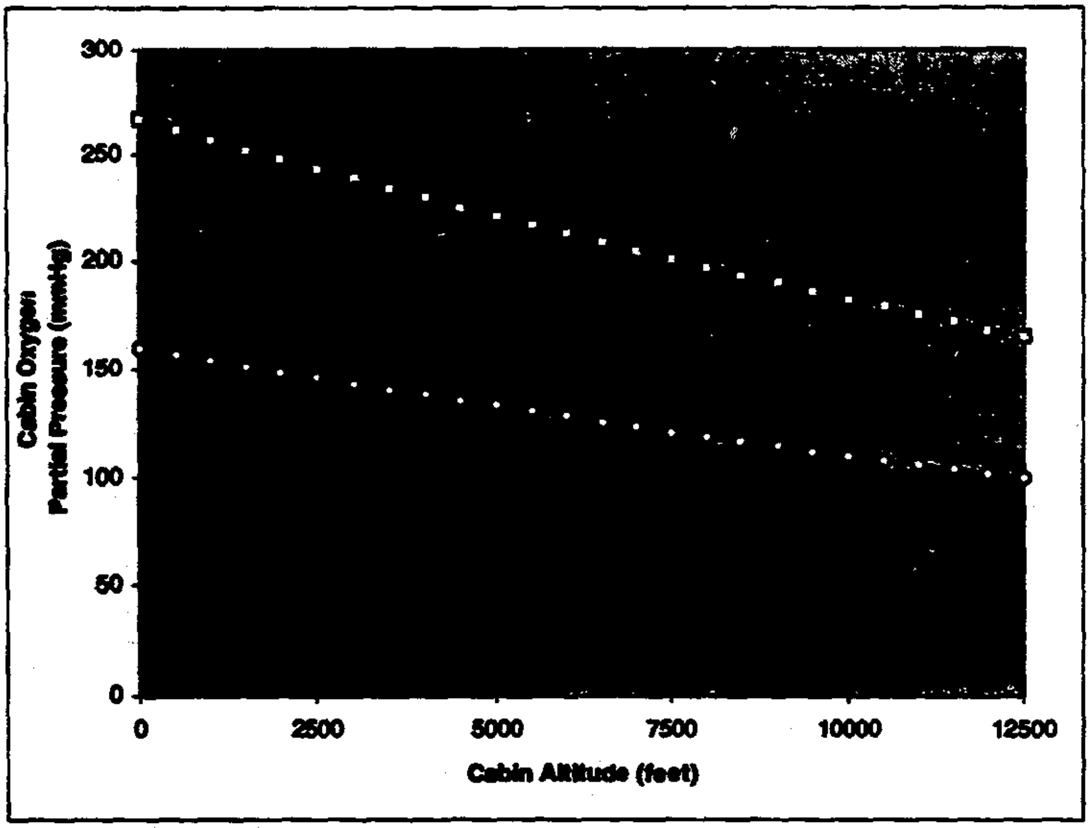

Figure 3. Creation of a hyperoxic environment offers a potentially large range of cabin pressurization levels. Square boxes—atmosphere containing 35% O_2; Circles—atmosphere containing 21% O_2.

5.1.2 Double Hull Cabin

Construct the aircraft with a double hull design. Anticipated to be more costly and heavier than a single hull design, the chance of a catastrophic decompression should be significantly reduced. There is also the potential that some type of insulator/sealer could be used between the hulls that could attenuate the flow of air out of occupant compartments in the event of disruption of the aircraft's wall. A drawback of the double hull solution is that it does not address decompression problems resulting from failure of mechanical components of the pressurization system.

5.1.3 Ram Air Injections after Failure

A mechanism for providing physiological protection through cabin repressurization is a ram air system. A ram air system consists of an extendable high recovery air scoop designed to collect ambient air and divert it into the aircraft to pressurize the cabin. A problem with this type of system is the enormous amounts of heat produced in the process. Therefore, the air must be cooled. Cooling can be accomplished through the vaporization of water. It has been estimated that repressurization to a cabin altitude of 20,000 feet during descent from a decompression at 70,000 feet would require 150 pounds of water (27). This increase in weight would not seem to be a significant penalty, particularly when considering that the same water could be used in a safety system that would extend evacuation times in case of a cabin fire emergency on the ground.

5.1.4 Manipulate the Cabin Atmosphere

Create a hyperoxic cabin environment. It has been estimated that transport cabin atmospheres could safely tolerate oxygen levels of approximately 35% in the range of acceptable cabin altitudes. The PO_2 in an enriched environment is graphed in Figure 3 with the partial pressure of oxygen in a 21% oxygen environment. The PO_2 of the enriched environment exceeds the sea level PO_2 up to a cabin altitude of approximately 20,000 feet. Oxygen partial pressure data related to increases in the percentage of oxygen in the cabin is listed in Table 3. An operationally functional example of this approach was the use of a 60% O_2 atmosphere in the crew capsule of the prototype XB-70 high altitude supersonic bomber. The oxygen level allowed a cabin altitude of 27,500 feet while

Altitude (feet)	Atmospheric Pressure (mmHg)	Oxygen Pressure (mmHg)			
		@ 21% O_2	@ 25% O_2	@ 30% O_2	@ 35% O_2
0		159	190	228	266
5,000		132	18	190	221
8,000		118	141	169	198
10,000			131	157	183
12,500			118	142	166
15,000				129	150
17,200				118	137
20,000					122
20,750					118
25,000					
30,000					
35,000					
40,000					
45,000					
50,000					
55,000					
60,000					
65,000					
70,000					

Table 3. Oxygen partial pressure changes resulting from increases in oxygen concentration.

oxygen partial pressures remained at or above sea level values. However, exposures of humans to atmospheres containing more than 50% oxygen for many hours can cause problems. Considering manipulation of the oxygen concentration in the cabin to be a functional scenario, the optimal pressurization / oxygenation level required would have to be identified. It has recently been suggested that pressurization of the cabin to 8K at 24% oxygen would be an acceptable approach for providing the equivalent atmospheric PO_2 of a 5,000 feet exposure under natural ambient conditions (21).

5.1.5 Compartmentalization of Cabin

The cabin could be divided into compartments that could be individually sealed automatically in the event an area of the cabin wall was penetrated. One drawback of this approach is that decreasing the volume of the area being decompressed significantly increases the severity of the event. Therefore, the well-being of the individuals in the area of the decompression is being conceded. Although unfortunate for these individuals, the compartmentalization approach may represent the most effective way to keep injuries and deaths resulting from decompression at a minimum. An alternate approach to compartmentalization is to have an independent or redundant pressurization system for the flight deck. The benefits of encapsulation of aircrew for the improvement of commercial flight safety at altitudes above 40,000 feet have been presented previously (14). It was hypothesized that, if the crew were capable of starting descent immediately, then the effects of the decompression, from the extreme altitudes would be survivable for the passengers if a ram air repressurization system and supplemental oxygen were also available.

5.2.1 Individual Protection

The implementation of personal devices for protection against a decompression event in an aircraft flying in the range of 60,000 to 80,000 feet must be considered in the context of the approach used for cabin pressurization. One approach is to assume that the pressurization system will never fail. Therefore, no protective breathing equipment would be necessary for any of the aircraft occupants. Another approach would be to outfit all occupants in pressure suits similar to those used in current spacecraft. The best solution probably lies somewhere between these two extreme approaches. Whatever protective equipment is utilized, its implementation must be a function of human intolerance to extreme altitude. Approaches currently used to protect individuals are discussed below in the context of potential use aboard an aircraft such as the HSCT. An underlying assumption of the discussion is that the crew will not be mentally or physically impaired at any point during a decompression event so that proper emergency procedures can be followed. Conditions that allow passenger survival are currently, and anticipated to be, the ultimate standard that protective equipment must meet.

5.2.2 Pressure Breathing

Given the proper physiological protection, humans can survive decompression to 80,000 feet (15). However, such exposures require positive pressure breathing at 70-80 torr, accompanied by G-suit counter pressures of 280-320 torr. Decompressions to 60,000 feet using only a pressure breathing mask and regulator have been found to be survivable in an experimental setting, but it is questionable whether or not adequate functional abilities would be maintained for piloting an aircraft (3). Furthermore, these studies have been done using highly fit individuals specifically trained in pressure breathing maneuvers. It is unlikely that the commercial pilot population, on average, could pressure breathe at these levels even if the proper equipment were available. Pressure breathing systems are currently installed on some aircraft. Federal Aviation Regulations (FARs) do not contain a pressure breathing limit schedule. However, a pressure schedule for altitude exposures up to and including 45,000 feet is contained in Technical Standard Order (TSO) C89, *Oxygen Regulators, Demand*. The positive pressure range permitted under this TSO for 45,000 feet exposure is approximately 20 to 25 mmHg. This represents an equivalent altitude exposure in the 5,000 feet range. If a 10,000 feet limit were acceptable, the same positive pressure limits would provide protection to an altitude of approximately 50,000 feet.

In the context of the diverse physical and medical conditions anticipated present in the passenger population flying aboard this type of aircraft, the use of pressure breathing as a means of protection for passengers probably is not a viable solution. Even if a system were designed that could be successfully implemented aboard the aircraft, training the individual passengers to properly use the system would not seem possible.

At a minimum requirement, pressure-breathing capabilities aboard the HSCT should be maintained consistent with equipment currently installed aboard passenger aircraft. Estimates of alveolar oxygen partial pressures must be examined in terms of an equivalent altitude exposure acceptable in an emergency situation. Positive pressure breathing schedules could be made more physically demanding. This would offer greater protection from hypoxia but would also dictate that specific training and physical fitness levels be incorporated into qualification standards for HSCT aircrew. Raising the pressure limits for positive pressure breathing would need to be supplemented with the use of pressure suits, as discussed in the following section.

5.2.3 Pressure Suits

It would be possible to place each HSCT occupant in a partial or full pressure suit. To accomplish this would require relatively extensive training of both the passengers and crew. The costs of the suits and associated equipment would appear to be prohibitive. Use of pressure suits would also place restrictions on the number of people competent to fly aboard the aircraft. Therefore, extensive use of pressure suits as a means of individual protection is not feasible for passengers, and it should only be considered for crewmember protection in the context of use with pressure breathing.

Many of the untoward effects associated by positive pressure breathing are attenuated by the use of full or partial pressure suits to provide counter pressure to the body. Considering the capabilities of the HSCT, use of partial pressure suits by crewmembers seems to be a reasonable precaution. Pressure garments specific to use aboard the HSCT should be developed for both flight deck crew and flight attendants. Ideally, the pressure level exerted by the garment should be controlled automatically as a function of ambient pressure and the positive pressure being delivered by the oxygen mask regulator. Pressure suits currently used in military operations could be used as a template for the development of functional civilian equivalents.

5.2.4 Oxygen Breathing Systems

Current transport category aircraft may be equipped with either pressure demand or demand oxygen masks for flight deck crew and continuous-flow oxygen masks for flight attendants and passengers. Current aviators' oxygen mask and regulator systems represent the minimum standard for flight deck crew use aboard the HSCT. The continuous flow systems currently utilized for flight attendant and passenger use, must be improved.

Decompressions to altitudes above 50,000 feet result in unconsciousness, even if the individual is breathing 100% O_2 (18). Therefore, a minimum of one flight deck crewmember should have an oxygen mask donned and breathing 100% O_2 whenever the aircraft's flight altitude exceeds 42,500. Pressure breathing should commence automatically in the event of decompression.

It is anticipated that the aircraft will be engineered to eliminate the possibility of the cabin altitude exceeding 45,000 feet without the occurrence being deemed catastrophic.

It may be necessary for flight attendants to carry a portable emergency oxygen system with some level of pressure breathing capabilities. The system must be designed so that it can be donned and operational in four to five seconds. It is anticipated that fully functional flight attendants would be of particular importance for passenger survivability in the event of decompression aboard the HSCT. Flight attendants should be available to assist those who fail to properly utilize the passenger protective breathing equipment available.

Continuous flow oxygen equipment appears to be the only viable protection that can be offered the passengers. However, the current system must be improved. A better fitting mask that is simpler to don is desirable. The positive effects of a face shaped mask have been documented (13). This study suggested a favorable influence on both recognition of a decompression emergency and correct donning by face-shaped masks. Some have argued for a portable mask/hood system, which not only supplies oxygen, but also offers protection from environmental contaminants that may be present. It is not clear whether the ability to wear such a mask during evacuation from an aircraft is a benefit. Certain is the fact that not all individuals will properly use protective equipment available to them in an actual decompression emergency. Therefore, a passenger mask that could be easily and quickly put in place by another person is highly desirable.

6.0 SUMMARY

A fleet of supersonic transports is recognized as a worthwhile goal for civilian aviation. The technology required for building such an aircraft has long been available, as is evidenced by the Concorde. However, a variety of economic factors have made it difficult to justify the development and widespread use of a domestic supersonic carrier. Review and analysis of HSCT issues indicate that modern technologies will allow the development of a high altitude supersonic aircraft that is economically viable. Such analysis includes rational solutions for the problem of accidental decompression. The use of a combination of protective strategies is necessary. At a minimum, it would appear that increased structural integrity of the cabin, a repressurization system, and an optimally designed supplemental oxygen system for crew and passengers are required.

The debate regarding safe altitude exposure levels for passengers must be addressed. Discussions among regulatory agencies, academia and industry as to whether or not rules that presently form the framework for FAA regulations represent a rational safety standard in the context of current and future passenger aircraft must continue. TUC and TSU could be addressed by a joint FAA, NASA, other government agencies, academia, and industry evaluation to determine an appropriate standard.

Previous experience with high altitude and high-speed flight must be built upon for the efficient development of an aircraft consistent with the design and implementation of the HSCT. Therefore, NASA High Speed Research resources should be used to support research in the areas of (a) physiological response of passengers and crew to rapid decompression at altitudes typical of a HSCT at cruise, and (b) advanced cabin materials to ascertain responses to internal and external loads associated with a HSCT. Such support is an example of how public and private sector resources can be integrated to ultimately build a successful HSCT program.

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