HUMAN FACTORS IN RELATION TO THE DEVELOPMENT OF PRESSURIZED CABINS

THE SIXTH ARMSTRONG LECTURE OF THE AEROSPACE MEDICAL ASSOCIATION

by

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Presented at the 42nd Annual Meeting
Aerospace Medical Association
Houston, Texas

April 28, 1971

Acknowledgments

It is appropriate at this time to acknowledge the inspiration and encouragement from General Harry Armstrong as a friend and colleague, going back to the time he was directing the Aeromedical Research Laboratory at Wright Field (1935). It has also been a great pleasure to work with General Armstrong and many other aerospace physicians in the military services and the civilian airlines.

It has been of special interest to follow the increasing scientific value of these annual meetings, having missed only one since this Association was originally founded. The quality of the publications through its own journal and other sources has resulted in many outstanding contributions to modern medicine and related disciplines.

The author would also like to take this opportunity to acknowledge the generosity of Harry F. Guggenheim and The Daniel and Florence Guggenheim Foundation for assistance in developing the Program in Aerospace Medicine at the Harvard School of Public Health. Aviation has lost a devoted friend of flight safety on the occasion of Mr. Guggenheim's untimely death on January 22, 1971.

The young physicians who have attended Harvard during the past twenty years have been a constant source of inspiration as colleagues and friends. Many of them have made outstanding contributions in their publications or their activities in aerospace medicine as well as in occupational medicine and public health.

It would be impossible to mention all of those former students who have been of help in one way or another. Special reference in connection with this lecture, however, is due to the late Julian Ward for his original work on Ebulism, to Charles Berry for his paper on on Dysbarism, to Kenneth Cooper in preparing a monograph on The Physiology of Flight, and to Carlton Peterson who has written an informative report on The History of Pressurized Cabins.

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HUMAN FACTORS IN RELATION TO THE DEVELOPMENT OF PRESSURIZED CABINS

I. Introduction; Objectives of the Lecture

One of the most important features of modern air transportation relates to the benefits which have been derived from pressurized cabins. This appears to be true, not only because of providing greater comfort and safety for the passengers, but also in enabling the aircrews to maintain a higher degree of efficiency in flying around or over adverse weather and in maintaining more regular schedules. The great increase in the number of passengers using this mode of travel and the remarkable safety record on a world-wide basis are undoubtedly related to the advantages of pressurized equipment.

One of the primary objectives of this Lecture is to highlight some of the more important human factors in the history of this feature of aircraft design. In tracing some of these developments, it will be possible to show how many of the important advances were made by aerospace physicians and those scientists working in closely related disciplines.

Many of us have often wondered why the great advantages of pressurized cabins were not realized sooner because of the many advantages to flying at high altitude, especially above 25,000 feet. In view of the wide acceptance of pressurized cabins in more recent years, it is hard to realize that the chapter on High Altitude Operations and Pressurized Cabins in the author's book on design published in 1946 had to be devoted chiefly toward arguments concerned with the safety, comfort and efficiency of this design feature. (1) Undoubtedly, the development of the jet engine which is known to operate most efficiently in rarefied atmosphere furthered this feature for both military and civilian air transport operations. Since there was great apprehension during World War II relating to the sudden loss of pressure from gunfire, pressurized cabins were delayed in development. Operating experience has proved, however, that this was not so serious as originally expected, especially for air transports. To be sure, difficulties were experienced, but at the present time many of the problems have been overcome. In fact most of those relating to the strength of the fuselage doors and windows have been solved, without too serious weight penalties. Problems relating to the operation of the pressurized system itself, or human limitations in controlling it, appear to be one of the limiting factors at the present time. An analysis of incidents of loss of pressure while in flight will be reported later.

The author's interest in this subject developed from studying the effects of high altitude on human performance in the laboratory, beginning at Cambridge University in England in 1927-1928 and in the Andes in 1935. From 1937-1941 he carried out studies of the fatiguing effects of long flights first in flying boat operators over the Pacific and Atlantic routes and later over mountainous terrain in the U.S. and Central and South America. It soon became obvious from these studies that individual oxygen masks for crews and passengers were impractical. The best solution was seen to be related to pressurized cabins to as near sea level conditions as possible while in flight at altitudes high enough to ascend above adverse weather and mountainous areas.

The point of view to be represented here is well described in the foreword by Edward P. Warner in my book, Human Factors in Air Transport Design, dedicated to aeronautical engineers. "The modern airplane is a product of research, development and refinement in detail that no other structure or mechanism has matched. The results have been so remarkable that there is always the danger of forgetting that these extraordinary craft still have to be operated by men without imposing unreasonable demands or unnecessary strains on the flight personnel. Coupled with the test of operability is the test of popular acceptance of the service that the airplane offers..... Passengers will not readily patronize a vehicle that leaves them uncomfortable or exhausted, and while passengers may not understand, the conditions existing inside the cabin leave sensory impressions, they will be in no doubt as to the importance of the results. Although human factors have never really escaped the attention of aircraft designers, their evaluation and solutions have sometimes lacked the benefit of organized and systematic attack." (1) Aerospace physicians and human factors engineers have contributed greatly to the development of many features relating to the physiological and psychological requirements of pressurized cabins. Many problems remain to be solved, however, and it is of primary importance that an advance analysis be made of all aspects in the design and operation of aircraft so as to meet the human requirements of both crews and passengers.

In the following sections primary attention will be given to the early history of pressurized equipment with only passing reference to the early balloonists and physiologists who helped to define and solve the problems. Emphasis will then be placed on the initial program in the U.S. Army Air Corps beginning in 1920, and the subsequent developments here and abroad which resulted in a highly successful pressurized cabin and operating system. This program was greatly furthered by the work of General Armstrong and his colleagues at Wright Field. The developments which occurred during World War II will be given attention insofar as they both hindered and furthered the use of pressurized aircraft. Special attention will be given to the air transports developed for commercial operations and the related operating problems, the primary one being concern with loss of pressure while in flight at high altitudes. It will be possible to only highlight the excellent laboratory work which was carried out here and abroad on decompression sickness, time of useful consciousness, and physiological tolerance limits in the event of pressure failure. In this presentation emphasis will be placed on the initial or threshold effects of high altitude in relation to obtaining the optimal cabin altitudes for passengers and aircrew under all conditions of flight and the widely varying conditions of health and age in the flying public.

II. Early History of Flight, and the Need for Pressurized Equipment

The British Association for the Advancement of Science sponsored balloon flights to study the effects of high altitudes as early as 1862. For example, the Englishmen, Glaisher and Coxwell, ascended to approximately 29,000 feet in that year. (2) During this particular flight Mr. Glaisher noticed a series of strange symptoms, notably loss of visual acuity and hearing, paralysis of the arms and legs, and finally, unconsciousness. His companion's arms were also paralyzed, but he managed to pull the valve rope with his teeth and start the balloon downward. Both men recovered as the balloon descended, but this marked the first practical encounter with the dangers of high altitude flight.

The published accounts of this and other flights by Glaisher stimulated the study of increased and decreased barometric pressures by the French physiologist, Paul Bert, resulting in his classical studies in this field. In 1875, three Frenchmen ascended in a balloon called the "Zenith" which resulted in an accident with only Tissandier, a meteorologist, surviving. (3) Although they had learned the use of oxygen to prevent the effects of hypoxia, they had been warned by Paul Bert that the amount of be carried was insufficient. In order to preserve the supply they waited too long before using it, thereby losing insight into their physical condition. All three lost consciousness at 24-26,000 feet, and the balloon descended on its own after reaching 28,000 feet. This tragedy stimulated Bert to increased research activity resulting in his book on barometric pressure, and it is well known that he was the first to prove that the principal effects of high altitude are due to the partial pressure of oxygen. His work did not become well known, however, until more than 50 years after his death. The accounts of these early balloon ascents have stimulated many of us to measure more precisely the loss of various sensory and motor functions under controlled laboratory conditions on ourselves and others. Actually their impressions have proved to be essentially correct, and it may be stated with certainty that Bert's work laid the original groundwork for pressurized aircraft. (4, 5)

The classical studies of Haldane, Leonard Hill, Barcroft and others in the English tradition extended the work of Bert in low pressure chambers and at high altitude. They elucidated the respiratory functions of the blood and other physiological responses to oxygen want. Their findings showed clearly that rate of ascent and altitude attained, as well as length of exposure and the physical characteristics of the individual were important. They also pointed out that the effects of hypoxia are only one of several problems in ascending to great heights. Others are decompression sickness in its various manifestations, such as bends, chokes, and neurocirculatory collapse, expansion of trapped gases in the gastrointestinal tract causing abdominal pains, pain in the middle ear or paranasal sinuses associated with pressure changes, and temperature and humidity. Their work is too well known to this group, especially those of us who have had the pleasure of studying in England, to be discussed further at this time. However, some of these subjects will be referred to later in relation to the specialized studies in aerospace medicine and rapid decompression of aircraft.

It is of interest to note that significant advances were made in Russia relating to the effects of high altitude. As early as 1875 the Russian physiologist, Mendeleyev, in his book entitled On the Temperature of the Upper Atmospheric Layers wrote "for safety reasons the observer should be placed in an hermetically sealed bell containing air at normal pressure." (6) Armstrong regards this as one of the first treatises pointing out the need for pressurized cabins in high altitude flying. (7) The Russian work has been further reported by Bykov, et al., "High Altitude Aircraft Equipment," translated from the Russian in 1961. (8) The Russians also had their early balloon ascents, some of them ending in tragedy in which they attributed the effects to a reduction in the partial pressure of oxygen in the atmosphere. Apparently this finding was made independently of the studies of Paul Bert.

In 1910 Cruchet and Moulinier in France published a series of papers on air sickness in which they made the following very relevent observation. "As a matter of fact the (oxygen) problem will never be satisfactorily solved until crew and passengers sitting in an airtight cabin shall breathe at all altitudes an atmosphere practically identical with that at sea level." (7)

Early Flight Tests with Pressurized Aircraft in the U.S.

One of the earliest attempts to pressurize an aircraft in the U.S. was initiated in 1920 by the Army Air Corps at Dayton, Ohio. The first flight was made by Lt. Harold R. Harris, Chief of the Flight Test Section. He later became president of Panagra and contributed greatly to the development of civil air transportation in this country. As a friend and associate, Harold Harris has provided the author with a detailed account of this flight in a steel tank on June 8, 1921. (9) The two seats of a DeHaviland DH-9 observation plane were removed and the area filled with an oval pressurized compartment, or tank made of steel. The flight controls were located inside the tank which had 5 six-inch glass portholes through which flight instruments outside the tank could be observed. The aircraft was powered by a single Liberty engine, and the pressurization was from a propeller-driven unit on the wing. No controls for the pressurization unit were included in the cabin. After several attempts Lieutenant Harris was able to lock the door into place after ascending to 3, 000 feet. The supercharger had been designed on the expectation there would be leakage through the packing around the control cables, and the designers had increased the compressor capacity by 100% to be on the safe side. Shortly after the door was closed at 3, 000 feet altitude, pressure built up within the tank until the altimeter inside registered 3, 000 feet (reported elsewhere as 7, 000 feet) below sea level, although the outside altimeter showed the plane at 3, 000 feet above sea level. Also the temperature had reached 150^{o} F. Since there was no possible escape from the ever increasing pressure, he placed the plane in a slow glide and landed as quickly as possible. He reported that at no time from shortly after closing the door until the plane came to a stop did the cabin altitude vary from 3, 000 feet below sea level. Although others stated that he complained of pain in his ears, he actually could not recall any particular discomfort. He was wringing wet with perspiration on landing, which he attributed partially to his anxiety as well as to the high temperature in the cabin. No additional flights were undertaken with the equipment described above because of other priorities in the subsequent time.

It is unfortunate that General Harris could not be present today to tell you of this flight which has excited and amused so many of us through the years. We are thankful that he survived to contribute to aviation in other ways, and especially to flight safety, which has become one of his main interests in recent years.

Between 1931 and 1937, beginning with Professor A. Piccard, a number of balloon flights were made in pressurized gondolas to altitudes as high as 72, 000 feet. These successful high altitude ascents proved that life could be supported through the use of pressurization. However, the pressure gondolas and pressure suits, to which many of the members of this Association contributed so brilliantly, were not practical for use in commercial aviation. Significant developments were made, however, in aerospace medicine by these high altitude ascents. (7)

Another early ascent with a pressure cabin airplane was made on 5 August 1935 by Marcel Cogno of France. He ascended to 32, 000 feet in a cylindrical pressure cabin, and after a few minutes at that altitude, he descended to 30, 000 feet and continued to fly for about 30 minutes. Suddenly the aircraft fell and crashed, and it was surmised that a window of the pressure cabin may have blown out, perhaps from a sudden buildup of pressure during failure of the cabin exhaust system. The autopsy of the pilot revealed that a cerebral hemorrhage occurred, as well as bilateral ruptured eardrums. The value of an autopsy in helping to determine the possible cause of a serious accident is brought out in this tragic incident. (cf 7)

The Army Air Corps initiated a second pressure cabin airplane project in 1935 to which General Armstrong made significant contributions through the aeromedical research program at Wright Field. (10) It was found that the physiological requirements could be satisfied by increasing the partial pressure of the oxygen in the compartment through an increase in the pressure of the contained or introduced atmosphere. The principal findings of Armstrong's study, completed in December 1935, were incorporated in the XC-35 delivered in 1937. The flight tests carried out during 1938 were completely successful, and the essential features were soon adopted in both military and civilian aircraft for flight at high altitudes. The success of the XC-35 was widely acclaimed. (cf 7)

<u>The Desire to Obtain Higher Operating Altitudes in Airline Operations</u>

Between the period of 1935 and 1940 the operators of long-range air transport routes such as TWA, PAA and BOAC became aware of the need to fly at increasingly higher altitudes as routes were extended over mountainous areas, and as the performance of aircraft was increased, the advantages of obtaining greater height became recognized. A number of accidents which occurred in the mountainous areas of the western part of the U.S. suggested the need for pilots to inhale oxygen. Also, the long-range operations in the north Atlantic could be made with increased safety, regularity of schedule, and passenger comfort at 20,000 feet and above. Information from the U.S. Weather Bureau and flight tests indicated that more favorable conditions could be obtained in regard to turbulence, adverse winds, and icing conditions at 20-25,000 feet altitudes. The substrosphere flying tests by Tomlinson of TWA and others in the field of pressure-pattern flying in 1935-1936 brought out the need for obtaining higher operating altitudes. It was shown that at 20,000 feet clear weather could be obtained in 95% of the flights and clouds could be readily avoided by making only inconsequential detours. (1, 11)

The results of these various studies brought out the fact that (1) oxygen is required at altitudes above 10,000 to 12,000 feet for prolonged flights, (2) the conventional methods of supplying oxygen presented space and weight problems, (3) the storage of oxygen under pressure or in liquid form involved certain dangers, and (4) there were many inconveniences for the passengers and crews in wearing masks. Also, it was discovered that the weight of the oxygen equipment in North Atlantic operations approximated 1,500-2,300 pounds, depending on the number of passengers. The need for pressurized cabins became even more apparent based upon careful studies of the safety, comfort, and operating efficiency. (See Table I) (1)

The Development of Air Transports with Pressurized Cabins

The above developments in regard to long-range, high-altitude flight brought out the need for air transports with pressurized cabins. Contracts were placed with the Boeing Aircraft Company to build the four-engined B307 Stratoliner. Mechanical compressors were produced by the General Electric Company and were engine-driven by extension shafts installed in the numbers one and four nacelles. The design pressure differential was an 8, 000 foot cabin altitude at a 15, 000 foot airplane altitude. Above 15, 000 feet the pressure differential remained constant at 2. 5 p. s. i. so that at 20, 000 feet the cabin altitude would be 12, 400 feet. Armstrong was an observer on three flights of the B307 operated by TWA, and he reported on the 24th of May 1940 that the pressure equipment operated satisfactorily and created comfortable conditions in the cabin during flight at 18, 000 and 19, 000 feet totaling 15 hours, 25 minutes. (6, 12)

Similar studies were made by the author in 1940 as an observer on a B307 transport plane purchased by PAA, operating through Miami, Brownsville, Texas, and Central America. During one of the flights a window was purposely broken out to see what would happen! A number of objects of no value suddenly disappeared through the window. The most interesting factor which occurred suddenly was the fogging of all of the windows and cabin from the rapid change in temperature. (13)

There was general agreement from the above tests with the B307 that the cabin pressure differential of 2. 5 p. s. i. was too limited and that oxygen masks would be required for crew and passengers in flights above 20, 000 (cabin altitude 12, 400) feet.

A conference was held at the Harvard Fatigue Laboratory in 1939 in which General Armstrong participated. At the timeof this conference on high altitude flying a B307 was flown from Seattle to Boston, and the well-known B-L-B mask was introduced for airline use by Walter Boothby and Randolph Lovelace. In a later Boeing model, the B-29, a cabin altitude of 8, 000 feet was maintained up to 30, 000 feet at a pressure differential of 6. 55 p. s. i. Also more adequate provisions for cooling were obtained in subsequent models and adjustable selective regulators were provided in later air transports (L-49, B-377, C-97, DC-6 and DC-7). For flights of more than three hours duration, a pressure differential of 7 p. s. i. was recommended at that time which would provide a cabin altitude of 8, 000 feet up to 35, 000 feet flight altitude. (14)

The Use of Pressurized Cabins During World War II

Several of the major air forces developed planes with pressurized cabins during World War II. There were wide differences of opinion in regard to including this design feature in both combat and transport equipment because of apprehension over loss of pressure from gunfire. Only a few examples will be given, based on first-hand observations. The Germans had placed a small supercharged cabin large enough for two pilots in the front of JU-86's for reconnaissance flights over Egypt at 40,000 feet and above when Rommel's forces were about to enter Cairo (August, 1942). The author spent some time with a Spitfire Squadron trying to intercept the JU-87's with aircraft and oxygen equipment limited to about 35,000 feet. It was necessary to strip down the Spitfires to save weight and in the final stages of attack dump fuel and ammunition to reach 40,000 feet, which they finally succeeded in doing. Imagine yourself getting into a fighter plane at 120° F in the desert and ascending to about 35,000 feet in 20 minutes where temperatures are 50° F below zero and at the same time suffering from hypoxia and aero-embolism. The Spitfire pilots were finally successful in their desert operations. The leader of this squadron, who was 37 years of age, suffered from a severe coronary with psychotic manifestations. Whether these flight operations under these extreme conditions formed the basis of his illness will never be completely determined. The author is aware of two other similar cases of cardiac distress and mental confusion which may have resulted from flights at very high altitude without proper oxygen equipment. However, they may have had a predisposition to heart disease.

Studies were made by the Flying Personnel Research Committee of the RAF during 1940-1941 in regard to the most desirable pressure differential for combat aircraft, i. e., 7-9 p. s. i., compared with 2.5 to 3 p. s. i. There were several physiological disadvantages of the high pressure system in combat at altitudes above 35,000 feet in case of a ruptured cabin, such as greater occurrence of decompression sickness, possibility of disabling abdominal gas expansion, brief time of useful consciousness and likelihood of forced descent to 20,000 feet or below with loss of pressure. The low pressure system would require the crew to use oxygen continuously above 17,000 feet, but some of the problems would be obviated. This system was recommended for combat aircraft such as the slower, and less well armored bombers. On the other hand it was recommended that commercial aircraft adopt the high pressure system since the risks of puncture would be less in non-combat zones. (6, 11, 15)

The decision was made by the War Production Board in the U.S. that transport planes such as the L-49 and DC-4 were not to use pressurization although they were designed for it. In spite of views expressed to the contrary on the part of the author, Randolph Lovelace and others, pressurization was not allowed in military transports. Our contention was that there was less likelihood of transports being attacked and the oxygen equipment was needed on long flights. This was especially true for patients being flown from the Pacific and other combat areas and cargo being flown over the Himalayas. Also many other obvious advantages would be lost. However, when the B-29 was developed for the Japanese campaign, a pressurized cabin was incorporated as an essential feature for greater range and ceiling. To be sure some difficulties were encountered with sudden loss of pressure in military aircraft as will be reviewed later. In general, however, this feature has been widely accepted currently for both combat and transport aircraft in the military services.

III. Studies of the Effects of High Altitude in Relation to Aircrews and Passengers

A satisfactory solution relating to the determination of optimum cabin altitudes presents an interesting problem in the field of human factors engineering and aerospace medicine. It is possible that considerations relating to increased weight may have been of more concern to the aircraft designers and operating airlines than the effects of high altitude on crews and passengers. Also how was the decision made to have the cabin altitude at 8,000 feet? One of the factors which led to the decision of 8,000 feet cabin altitude was the realization that there are a number of airports in South America, and a major one such as at Mexico City, at approximately this altitude. Currently there is increased interest in having cabin altitudes nearer sea level, or between 3,000 and 5,000 feet, rather than 6,000 or 8,000 feet. This is due to the fact that many airline passengers are in the older, or very young age ranges, with a certain percentage having a significant amount of illness. In addition, it is known that alcohol will accentuate the effects of altitude, and the carbon monoxide from cigarette smoking will lower one's ceiling. It is possible that some of the fatiguing effects of long flights and crossing time zones may be due to the interaction of these factors. A brief review of the experimental evidence from the effects of moderately high altitude will be presented below. In other words, it is relevant to determine the threshold effects of hypoxia, or the altitudes where sensory or cognitive functions are first influenced and where the impairments may become more severe. (13)

Results from Early Investigations in Establishing Tolerance Limits for Airmen and Air Transport Passengers

Some of the earliest studies on airmen were made with rebreather devices for establishing altitude tolerance limits for pilots in the first World War. In these tests each pilot rebreathed a given volume of air, thereby progressively reducing the oxygen supply. The experiments lasted 20-30 minutes, and very high simulated altitudes were reached, i.e., up to 25-28,000 feet. The point of collapse, taken as the tolerance level, was much higher than if the subject had been exposed to a more gradual "ascending" over a period of one to two hours. Many of these pilots later became transport airmen in the civil airlines. It was often difficult to convince them that they needed to inhale oxygen at much lower altitudes than the altitude classification tests (or point of collapse). In the second World War, the indoctrination tests in low pressure chambers were much more realistic and clearly demonstrated the need for oxygen at lower altitudes. Night flights or rapid ascents in military operations required use of oxygen from the ground up, based upon tests for night vision, as will be shown below. (13)

In the early history of commercial flying, the deteriorating effects of altitude on flight crews and passengers in the range of 10, 000 to 16, 000 feet were not fully appreciated. The pilots did not believe they were seriously affected, and the author observed fairly extreme reactions in the passengers and aircrews on trans-Andean flights, inaugurated in 1933. In these planes each passenger was provided with a tube from which he could inhale oxygen during the 20-30 minute flight spent at 15, 000 feet or above. This method of administration of oxygen was known to be very inefficient. A number of accidents in the mountainous regions of the west might have been caused by the insidious effects of oxygen lack on the performance of the pilots. The airline operators and especially their medical officers soon realized that as a safety measure each pilot should be required to use oxygen in the neighborhood of 10, 000 to 12, 000 feet on longer flights. The pilots themselves also became convinced of its value when they found it reduced their operational fatigue and improved their mental efficiency. (13)

An attempt was made to study the psychological effects of oxygen deprivation under carefully controlled laboratory conditions with Henry Barcroft at Cambridge University, England in 1928. (5) The subjects were fifteen students in the RAF University Air Squadron. They breathed oxygen mixtures simulating 14, 000 to 28, 000 feet for short periods of time. Each subject took a series of simple and choice reaction time tests and others involving pursuit tasks and reasoning. The results indicated that simple sensory and motor responses were not seriously impaired until the subject approached collapse, while the choice reaction times and pursuit tasks were influenced at lower altitudes. This was also true for the tests involving attention, memory and reasoning at the higher simulated altitudes. The changes in handwriting were very pronounced. Also with advanced hypoxia there were unusual alterations in mood and loss of insight concerning certain aspects of their altered behavior. These acute studies of hypoxia formed the background for a series of experiments in later years where the blood gases, glucose and other biochemical tests were correlated with a wide variety of psychophysiological ones.

These studies have been carried out in low oxygen and low pressure chambers at sea level, during flights in air transports, and on high altitude expeditions to the Andes and Rocky mountains. In this way it has been possible to measure the effects of oxygen want in both acclimatized and unacclimatized subjects under a wide variety of conditions.

In 1937 the Bureau of Air Commerce sponsored an extensive investigation on the effects of altitude on the average airline passenger at Columbia University under the direction of the author. Over 200 subjects between 18 and 72 years of age were studied in a chamber at sea level in which altitudes and rates of ascent simulated those used on domestic airlines. A series of physiological and psychological tests was given before each ascent, and repeated during the first and second hours. In addition, each person was asked to check a standardized list of complaints, and to record his or her subjective reactions. Many subjects were noticeably influenced at simulated altitudes as low as 10,000 feet during rapid ascents, while a larger percentage were affected at 16,000 feet. The results from one of the more sensitive tests, i.e., immediate memory, are shown in Figure 1. The most frequent complaints recorded voluntarily by subjects during rapid ascents are shown in Figure 2. Almost 40 percent of the subjects reported headaches at approximately 12,000 feet. (16)

Later it was possible to carry out studies of pilots and passengers on trans-Andean planes of Panagra and transcontinental flights of United Airlines. A very extensive investigation was made in 1937 on PAA flight crews and passengers during long-range operations between California and Hong Kong. The altitudes flown ranged between 8,000 and 12,000 feet. A complete series of psychological and biochemical tests were obtained by H. T. Edwards, a biochemist, and the author. This may have been the first, and possibly the only time, that arterial punctures were obtained during flight for determination of the blood gases. In general, the results indicated that there was little in the blood chemistry to suggest excessive physiological fatigue or intense emotional excitement. Also, the findings at the various altitudes were comparable to those obtained in chamber studies at sea level. (17)

Between 1936 and 1940 several other developments in the operating airlines stimulated greater interest in the human problems encountered in high altitude flying. Other studies here and abroad showed the need for oxygen, and the medical departments of the major airlines began to indoctrinate their pilots in its use. Also, more suitable breathing equipment for aircrews and passengers was designed under the leadership of the Mayo Clinic. As the need of safety measures was recognized and light-weight oxygen installations became available for air transport, it seemed practicable to set up regulations governing its use. In March, 1941, the CAB issued CAR 61.743 as follows: "Oxygen Apparatus and its Use. No air carrier aircraft shall be operated in scheduled air transportation at an altitude exceeding 12,000 feet above sea level for any length of time, unless such aircraft is equipped with an effective oxygen apparatus and an adequate supply of oxygen available for the convenient use of the operating crew, and proper use is made of such apparatus."

Experiments Relating to Thresholds of Impairment at Altitude

In studying the reports from the Medical Research Laboratory of the U.S. Army Air Service of World War I, the author became interested in verifying experimentally the observation that lights became dimmer while breathing gas mixtures deficient in oxygen, and brighter when a normal supply of oxygen was inhaled. This appeared to be true especially at low levels of illumination. In our laboratory at Columbia University in 1936-1937, dark adaptation curves were obtained on 20 subjects at sea level and again at approximately 7,000, 11,000, and 15,000 feet.(18) As can be seen in Figure 3 the impairment was very significant, and normal values were restored within three or four minutes upon inhaling oxygen. Later it was possible to repeat these investigations with more refined equipment, an adaptometer developed by Selig Hecht. These and other investigations on dark adaptation at the Harvard Fatigue Laboratory brought out the fact that impairment was present at altitudes as low as 4,000 feet. Similar results were obtained using tests for differential light sensitivity (foveal stimulation) as well as during experiments concerned with completely dark adapted eyes. Again it was clearly noted that these effects were greater at low levels of illumination. The implications for inhaling oxygen at night were very direct, and this proved to be one of the most sensitive tests for demonstrating the effects of oxygen want at high altitudes. (See Figure 4, a summary of visual tests in relation to hypoxia.)

In general, the studies relating to mental functions and various performance tests have not proved to be as sensitive, partially due to the effects of practice, or learning, on the part of the subjects. Some impairment has been noted, however, in tests for immediate memory as low as 6,000-8,000 feet. The results of a series of studies have been combined in Figure 5. Another response which has been observed by various investigators relates to the tendency for "mental blocking," as reported by Bills (19), or "looking without seeing," as observed by Mackworth. In our laboratory at the Guggenheim Center at Harvard, this phenomenon, termed "response blocking," has been under further investigation. It has been of interest in the analysis of accidents, where subjects have apparently failed to see, interpret, or react to obviously apparent or dangerous situations. Hypoxia is known to accentuate such reactions, as well as do alcohol and certain drugs which impair oxidation. (20)

In his recent book, Environment and Human Efficiency, Poulton has reported that subjects performing an orientation task at sea level, 5,000 feet, and 8,000 feet showed longest reaction times at the highest altitude, and significantly longer response times at 5,000 feet than at sea level. This effect disappeared, however, with increased learning of the task, suggesting that at 5,000 feet, tasks likely to be affected will be difficult situations met for the first time. (21)

It might be concluded from these and other studies that significant impairment may result at altitudes from 4, 000 to 6, 000 feet, if produced rapidly as in an airplane ascent and in unacclimatized subjects. Although these threshold values may be significant, it does not follow that this altitude should be interpreted as dangerous to the average person in aircraft cabins. This degree of hypoxia, however, may be of importance to passengers if combined with other influences such as alcohol, carbon monoxide, certain medications, and various conditions of health and age. (13)

The Effects of Altitude in Combination with Carbon Monoxide and Alcohol

In the early history of aviation the effects of carbon monoxide from engine exhaust was a significant influence. With the development of jet engines and pressurized cabins, the carbon monoxide from this source has been practically eliminated. The chief source of carbon monoxide for airline passengers is likely to be cigarette smoking. It is well known that small amounts of carbon monoxide from this source can inactivate a large amount of hemoglobin as an oxygen carrier, producing essentially an anemia. In other words, the effects of carbon monoxide and altitude are additive.

The effect of a given increase in carboxyhemoglobin is approximately the same as that of an equal loss of arterial oxygen saturation due to high altitude. On this basis one can determine the "physiological altitude" that results in the blood after smoking. (22) This is shown in Figure 6 for 5 and 10 percent saturations of the blood with carbon monoxide at sea level and at various true altitudes. Thus a person at sea level with 10 percent carboxyhemoglobin is affected in the same way as if he were at 12, 000 feet. The same amount of carboxyhemoglobin at 12, 000 feet altitude results in a combined effect equivalent to 16, 000 feet, thus lowering the "ceiling" by 4, 000 feet. We have developed nomograms to determine the combined effects or the "physiological altitude" of a subject. Since it has been established that the averate chronic smoker has from 4-8 percent carboxyhemoglobin in his blood, such persons would be at a considerably higher altitude physiologically in an aircraft cabin altitude of 6-8, 000 feet, and this would appear to be a basis for an air traveler to feel fatigued after a flight of several hours duration. Altitude tolerance tests in low pressure chambers by several other investigators have shown a significant lowering in performance compared to that on days in which subjects refrained from smoking. Pilots are becoming increasingly aware of this fact, since they have found that they feel less fatigued on long flights if they have refrained from smoking. (13)

In regard to the combined effects of alcohol and altitude, it is now well recognized that the effects may be additive. Alcohol exercises its primary physiological action by depressing oxidation in the cells. The impairment is believed to result from histotoxic influences, i. e., "the tissue cells are poisoned in such a manner that they cannot use the oxygen properly similar to narcotics which inhibit oxidation." This interpretation explains (1) the striking effects of alcohol on the nervous system and (2) why alcohol and oxygen want produce more serious effects on the nervous tissue and consequently on behavior if both are experienced simultaneously. Thus if a person ascends to moderate altitude with alcohol in his blood, he would be especially vulnerable to the effects. For example, the alcohol in 2 or 3 cocktails would have the physiological action of 4 or 5 drinks if taken at approximately 10-12, 000 feet. (13)

The synergistic action of hypoxia and alcohol has been demonstrated on the higher cerebral functions. In the Andean expedition we found that at 12, 000 feet the concentration of alcohol in the blood rose more rapidly and reached higher and more sustained levels than at sea level. In one subject the concentration of alcohol in the blood 12 hours after ingestion was three times greater than at sea level. Psychometric tests revealed the same synergism. Other investigators have obtained similar results relating to the combined effects of alcohol and oxygen want. (23)

In our laboratory at the Guggenheim Center we have been studying the effects of small amounts of alcohol on foveal dark adaptation. After two training sessions a control curve was obtained on each of 10 subjects. This was followed by drinking 2 ounces of commercial 80 proof vodka, giving rise to blood alcohol levels of approximately 0. 03 percent. Dark adaptation curves were obtained at approximately 10 minute intervals until 50 minutes had elapsed. The results are shown in Figure 7. The greatest decrement was found between the control curve and adaptation readings from 25-30 minutes later, when the concentration of alcohol in the blood was greatest. Therefore, alcohol, even in these small amounts, produced significant impairment.

The general conclusion to be drawn from this discussion of the effects of carbon monoxide and alcohol during flight is that some of the fatigue from long flights on the part of passengers may arise from these sources. The implication is that it would be advantageous to most passengers to maintain as near sea level conditions as possible at all flight altitudes.

The Effects of Altitude in Relation to Age

Another important variable in air transportation relates to the ages of those being flown as passengers. There is a great deal of evidence that infants and small children tolerate moderate altitudes very well. Also, it has been shown in previous studies (16) that older persons up to 72 years of age respond to moderate altitudes, i. e., up to 16, 000 feet, without unusual difficulties. Most of the low pressure chamber studies of rapid decompression have been made on healthy youthful persons in the age ranges of those in the military service. No extensive investigations have been reported on the way in which passengers over 65-70 years of age might react to acute oxygen want.

In an attempt to work out a theory of aging, the author has studied the similarities between the effects of high altitude and age on various sensory and cognitive functions. One is impressed by the fundamental role of oxygen in the metabolism of nervous tissue, not only during exposure to high altitude, but also in the processes of aging. It is interesting to note, for example, that the sensory and mental impairment which occurs in both normal and clinical subjects under experimental conditions of oxygen deprivation simulate very precisely the behavioral changes observed in the aging process. The author has reviewed the experimental evidence of the important role which oxygen plays in the functioning of the central nervous system on the processes of aging. (24)

As indicated previously one of the most sensitive tests of high altitude relates to measurements of light sensitivity, especially at low levels of illumination, or in obtaining a curve of complete dark adaptation. It has also been observed that this decrease in ability to see at low levels of illumination gives rise to one of the highest correlations in the aging process. Dark adaptations were obtained on 240 subjects varying in age from 16-90 years. It was found that there was a high degree of difference in sensitivity between the very old and the very young, and the intensity of a point of light for the dark adapted eye had to be approximately doubled for every 13 years of age to be seen. In Figure 8 the influence of age on the final points of a dark adaptation curve have been plotted in relation to values obtained from exposures to high altitude. (25)

Another example of the striking similarity between the effects of high altitude and the changes which occur with aging will be taken from the field of memory. It is well known that older persons are poorer in this function than younger ones. These reactions have been studied with the method of paired associates for both meaningful words and nonsense syllables both at sea level and at high altitude. (Figure 9) The similarity of the results obtained are very striking indeed.

Other studies have also been carried out in regard to the problems which have arisen at high altitude, not only during the period of gestation and at birth, but also during the period of development and growth through adolescence and maturity. The influences of oxygen lack during the first trimester or the organo-genetic period is most critical. Ingalls (26) exposed mice to altitudes of 27,000 to 30,000 feet during the complete reproductive cycle. He observed multiple skeletal deformities, cleft palate, mongolism, and other abnormalities which were attributed to the acute hypoxia in the mother and fetus. The basic physiology of the role of oxygen in fetal behavior is well established. Blindness in children (retrolental fibroplasia) provides another example of a response of immature neural tissue to hypoxia.

Although an analysis of the basic physiochemical mechanisms underlying the aging processes is beyond the scope of this presentation, in hypoxia and aging there is a diminished availability, or utilization, of oxygen in the central nervous system. This may be due to either or both of the following causes of interference with normal metabolic processes within the individual cells: (a) a reduced rate of oxygen transfer to the cells, or (b) inadequacy of cellular enzyme systems. Transference in turn may be inadequate because of reduced oxygen supply, reduced circulatory delivery, or slower diffusion. (24)

It has not been possible to demonstrate an improvement in sensory or cognitive functions in the elderly by administering 100 percent oxygen. However, recent experiments have reported that hyperoxygenation at 2.5 atmospheres in a hyperbaric chamber while inhaling 100 percent oxygen has suggested an improved performance that persisted in subjects aged 70-75 years over significant periods of time. (27)

It should be emphasized that the effects of high altitude and aging are not necessarily additive, as has been indicated above in the case of carbon monoxide and alcohol. As stated above, elderly persons are known to be excellent air travelers. It is perhaps only the elderly person who may be suffering from respiratory or circulatory illness who might receive adverse effects from sudden and acute hypoxia during loss of cabin pressure at high altitude.

Designing for the Most Desirable Cabin Altitude for Air Transports

In recent years there has been a tendency for aircraft designers to maintain a cabin altitude of 6,000 feet at the higher cruising altitudes. For example, the Boeing 707, the Douglas DC-8, and the British VC-10 maintain approximately 5,000 cabin altitude while cruising at 35,000 feet, a distinct improvement over previous models. Some years ago it was estimated that pressurizing for 6,000 rather than 8,000 feet would require an increase of 750-1,500 pounds for a 60-100 passenger aircraft, with this added weight at an initial cost of $40 per pound. With the more recent advances in metallurgy, these weight and cost estimates may be considerably reduced. * The human factors analysis presented here would suggest that the comfort and well-being of airline passengers would be significantly benefited by as near sea level conditions as possible. In any event, cabin altitudes of 3,000-5,000 feet should not be exceeded.

A study entitled "Biomedical Considerations for Passengers in Relation to Cabin Decompression" has been made by the Douglas Aircraft Company (Memorandum report no. 61, April 8, 1965). The objective was to estimate the frequency of various diseases occurring in the U. S. population who might be flying now and in the future. The data were from the National Health Surveys of the USPHS. Although precise figures could not be projected for the air-traveling public, it was obvious that a large number of persons with chronic or acute respiratory diseases and circulatory disorders use this mode of travel. Maximum cabin altitudes of 3,000-5,000 feet would clearly be advantageous for such passengers.

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* Piston Powered Aircraft can achieve long range at low altitude by flying slowly (at best lift/drag ratio) so that aircraft drag is minimized. However, speed can be increased by flying at higher altitude without sacrificing range (in fact usually with a small improvement due to flying at somewhat higher power where the engine may be more efficient). This increase in speed is usually limited by the amount of supercharging available for the engine and for the cabin (in transports).

Turbine Powered Aircraft (including jets) <u>must</u> fly at high altitude for long range. Efficiency of such engines is strongly dependent on the ratio of turbine inlet temperature to ambient temperature, and turbine engines can be operated at part throttle (low turbine inlet temperature) only with severe penalties in efficiency. In addition to the aerodynamic benefits which can be derived from flying at low atmospheric density, turbine powered craft derive great advantage in engine efficiency from flying at high altitude (up to the tropopause) where the ambient temperature is lower.

Jet Powered Aircraft are relatively inefficient during take-off. They tend to use large engines to ease this problem. This, and their ability to fly at high speed, makes it desirable to cruise at still higher altitude.

Thus cabin superchargers are advantageous for piston aircraft, still more necessary on turbo-propeller machines, indispensible for turbo-jets and supersonic aircraft are unthinkable without them.

IV. The Influence of Changes in Barometric Pressure on Human Subjects

A decrease in barometric pressure, in addition to giving rise to oxygen want, has other undesirable effects on the body. The symptoms are generally known as decompression sickness or dysbarism and may be classified according to whether they take place during ascent (decompression) or descent (recompression). They may also be grouped according to their cause, i. e., (1) the expansion of free gases in certain body cavities from which ready escape is not always possible, causing pain in the abdominal region, sinuses or teeth, or (2) evolved gases, principally nitrogen, which escape from solution in the blood and tissue fluids, giving rise to bends, chokes, and neurological symptoms. These disturbances, resulting from decompression from one atmosphere to less than one atmosphere are known as aeroembolism. A "family tree" relating to dysbarism is shown in Figure 10, in which the symptoms are classified according to whether they involve gases trapped in body cavities, evolved gases, or in response to rapid decompression. (28) In Table II the incidence of various symptoms of dysbarism is shown for subjects exposed to decreased pressure in altitude chambers. The figures in the table are given in terms of per 100 persons exposed.

Some of the most significant developments in aerospace medicine have taken place in studying the above symptoms as a result of high altitude flying and the development of pressurized cabins. The very thorough and carefully controlled experiments in this field have significantly advanced our knowledge of the human organism. No other subject in aerospace medicine has been of greater interest with the possible exception of zero gravity and certain aspects of acceleration. The studies which were made at the Aerospace Medical Laboratories at Wright Field under General Armstrong's direction are well known to the members of this Association. (7) Also the studies in England, Canada, France, and Germany have been of equal importance in advancing our knowledge of the responses of the human body to rapid loss of pressure on all types of aircraft. Only brief reference will be made to some of these classic investigations as they relate to specific problems in air transport planes carrying passengers. In addition to General Armstrong's textbook, the chapter on "Decompression Sickness" by D. I. Fryer and H. L. Roxburgh, and that on "Failure of Pressure Cabin" by D. I. Fryer in A Textbook of Aviation Physiology, edited by J. A. Gillies, should be consulted. (29) The tragic death of David Fryer in a car accident on March 16, 1971 has been a great loss to aviation medicine and to his friends and associates here and abroad.

As early as 1929 Jongbloed described dysbaric symptoms during chamber ascents to 42,700 feet. (30) Later, or about 1937, many experiments in the area of decompression were carried out when there was great increase in military airmen beginning to fly pressurized aircraft at high altitudes. Many of these investigations were concerned with the hazards of decompression of military aircraft. Also, there was concern for studying recompression rates simulating free-fall parachute descents, or emergency aircraft dives. These studies, as well as the ones in more recent years, have elucidated the symptomology and etiology of the decompression syndrome, including the subsequent hypoxic stress. The excellent review of this work by von Beckh should be consulted. (31) This chronological review of rapid decompression experiments with human subjects between 1939 and 1968 gives the essential findings, along with interesting notations and interpretations having direct implications for preventive measures in air transports. The time-of-useful-consciousness, and total "rescue" time after decompression are also applied to the more advanced high altitude supersonic aircraft. Many studies in this field are reviewed in the chapters on Hypoxia, Barotrauma, and Decompression Sickness in the second edition of Aerospace Medicine, edited by Hugh W. Randel. (32)

The Effects of Rapid Decompression During Flight

The development of pressurized cabins has proved to be one of the most successful aspects of modern air transportation, and with this design feature, it has been possible to provide passengers with a smoother flight by going over or around adverse weather and turbulence. Although high altitude gusts remain a problem, operating experience has shown that this occurs less frequently than anticipated. The smoother flights have resulted in a marked decrease in air sickness among airline passengers. Also the incidence of passenger discomforts in general have declined very significantly.

It was anticipated that cabin pressure failure might present serious problems to the aircrews and passengers. The first hazard in rapid decompression is the fact that the pressure gradient is equalized rapidly and with great force. If an astrodome, emergency hatch, or window fails, an individual sitting or standing near the opening might be swept out of the plane; such cases are on record in both civilian and military operations. Thus the importance of keeping safety belts fastened and the essential instruments and equipment securely attached at all times was emphasized.

A second hazard results from the direct effects of a very rapid rate of decompression. There are at least four important physical variables that must be considered: (a) the volume of the pressurized compartment, (b) the size of the opening, (c) the pressure differential, and (d) the flight altitude at which the decompression takes place. Naturally, the most drastic decompression possible would be that occurring in the smallest cabin with the lowest cabin altitude at the highest possible flight altitude. Experiments were made at Wright Field by Sweeney to test very extreme conditions in small military aircraft in flight at 35, 000 to 40, 000 feet. The results indicated that the averate subject experienced a sense of inflation in the chest and abdomen as a result of expanded gas, and about

20 percent of them suffered "bends" during the first 5 minutes at high altitude. These conditions were much more acute than would be experienced in transports with larger pressurized areas. (7)

By far the greatest and most serious hazard of a rapid decompression is that of acute oxygen want, since useful consciousness can be maintained no longer than about one minute at 40,000 feet. This is an important consideration at all altitudes above 25,000 feet. (Figure 11) The indicated time reserves in the figure are for subjects at rest and would be less for an active pilot carrying out a certain amount of emergency action. A potentially more serious problem of acute oxygen want exists (a) if a plane should be forced to remain at altitudes over 25,000 feet after loss of pressure due to weather or terrain, and (b) if sufficient oxygen is not available for all crew members and passengers.

At very high altitudes, the time for the onset of symptoms is very rapid, and the effects on the body are extreme. The relationship between altitude and the time for the onset of symptoms for healthy young males is shown in the figure. Such tests as card-sorting and handwriting were used as criteria of the time of useful consciousness, using subjects in low pressure chambers following removal of their masks. The time reserve is 29 to 49 percent longer in the mask removal than in the rapid decompression series. These latter findings are significant because they simulate more realistically the type of response that would occur during loss of pressure in an air transport while in flight at high altitude. (33)

In addition to the effects of oxygen want and aeroembolism, there are other variables that must be considered in high altitude flying. The effects of cold undoubtedly would be serious in some instances. Distention of the stomach and intestines might give rise to considerable disturbance, and persons with certain diseases of the heart or lungs or with anemia would experience severe reactions.

<u>Operating Experience in Military and Civilian Pressurized Aircraft</u>

It is of interest to note that during World War II a great deal was learned about the loss of pressure in combat aircraft and indeed many serious accidents occurred. For example, from August 1942 to May 1945, there were 388 non-fatal and 77 fatal cases attributable to oxygen want in the Eighth Air Force alone. During 1943 there were 21.6 deaths per 100,000 man missions. Table III summarizes the reported decompressions in the USAF during the period January 1, 1951 through April 30, 1955. The total number reported during this period was 98. It is evident from the breakdown by altitude that the majority of these decompressions occurred below 25,000 feet. The risk of dysbarism, therefore, was small. It can be seen from some of the reported crew effects that hypoxia, however, was still a factor at these altitudes. With improved indoctrination programs the death rate due to oxygen want declined to a level of 2 per 100,000 man missions by the end of the war.

The operating experience with pressurized air transports from 1950-1954 indicated that there was a sudden loss of pressure in one plane per 96,000 hours of flying. Most of these instances occurred below altitudes of 25,000 feet. In general, the number of rapid decompressions were less than anticipated.

The introduction of jet transports operating as high as 30,000-35,000 feet introduced a serious potential hazard, since the time of useful consciousness following cabin pressure failure at these altitudes would be less than a minute or two depending on (1) the age and physical condition of the passengers, (2) the size of opening, and (3) the volume of the cabin. Examples of forced descent patterns while in flight in relation to human tolerance limits are shown in Figure 12.

In the very early days of operating air transports with pressurized cabins, there were several fatalities involving persons being "sucked out" of the aircraft. For example, a navigator on a Constellation in the North Atlantic was ejected when his head struck the astrodome. Several cases of crew fatalities were reported from being ejected from cabin doors. In recent years the author is aware of no such cases with the greater integrity of fuselage structures. In the large number of incidents reviewed from 1959 through 1970, no fatalities were reported relating to cabin pressure failure with the exception of the tragic Comet accidents.

It has been stated by Fryer that no case of pulmonary injury resulting from explosive decompression in the air so far has been reported. This is in spite of dimensional factors of 3 to 4 in some aircraft when losing large transparencies and pressure factors of 2 to 6 or more. (cf 29) The explanation of this is that under completely unexpected cabin failure the chance of the glottis being closed is extremely small. In addition, most accidents have occurred in cabins at low differential pressures. In air transports the cabins are large and the area of orifice necessary to produce very dangerous conditions is correspondently large.

It is relative in this connection to consider the investigations of the disastrous loss of two British "Comet" jet airlines on January 10 and April 8, 1954. (34) Both aircraft were shown to have disintegrated at high altitude shortly after takeoff. Using Gagge's very conservative estimate of uncertain safety, it was shown that in order to exceed limiting conditions when flying at 30,000 (cabin pressure -7.5 lb./in.^{2} above atmospheric), it would require the instantaneous loss of 154 ft.^{2} of cabin wall. According to Violetto's curve (cf 35) of limiting conditions, the area may have been 290 sq. ft. equivalent to a hole of 17 ft. square. If the aperture was that large there would be an indication of the disintegration of the fuselage structure. The extensive investigations which followed the Comet accidents, involving placing the fuselage in water, brought out the probability that the above conditions took place.

It is of interest to consider the operating experience of jet planes in more recent years in regard to cabin pressure failure. In general, these planes have been remarkably successful in regard to the integrity of the pressurized cabins. Everyone is familiar with the drop-out oxygen equipment on current transports which is activated when the cabin pressure reaches about 10 to 12,000 feet altitude. In 1959 there were six instances of voluntary descents while in flight at 26,000 to 35,000 feet, chiefly due to cracked windows. In 1960 there were eight voluntary and six emergency incidents in flight. The causes were chiefly compression failures or cracked windows.

In a previous survey the author made an analysis of incidents relating to cabin pressure malfunctions in jet operations, U.S. registry only, during the period January 1959 through part of 1967. (36) The information was obtained from the Flight Standards Service of the FAA indicating a total of 114 incidents in this time. This information has been brought up to date through 1969, and part of 1970, covering a total of 240 reported instances. Of these more than half occurred during take-off and climb with the aircraft returning to base. Of the remaining incidents, many involved a precautionary descent from flight altitude, without rapid loss of pressure or the need for emergency procedures or use of oxygen equipment. Fewer than one-fourth of the total incidents represented rapid loss of pressure at cruise altitudes, emergency descents, and deployment of oxygen masks. The records are not complete enough to state how frequently cabin altitudes exceeded 13,000 feet. In Table IV the total number of depressurization incidents are shown for the years 1966 through 1969. The table also shows the approximate numbers involving (1) emergency descents from cruising altitude and use of O_2 mask, (2) precautionary descents due to threat of pressure loss or pressurization problems, and (3) those involving pressurization problems occurring during take-off and climb.

One of the most extreme instances in the series reported above occurred during the flight of a B707 from McCord Air Force Base, Washington, to Tokyo when the aircraft, one hour before destination, experienced loss of cabin pressure at 39,000 feet. Emergency descent to 7,000 feet was made, with deployment of cabin oxygen masks. Aircraft landed at Tokyo. Twenty passengers complained of ear pains and air sickness. One passenger became unconscious and was amnesic after regaining consciousness. Military physicians examined all 165 passengers on board. One hundred thirty-five were released and 30 were held for treatment of ear blockage. Two stewardesses lost consciousness while trying to help hypoxic passengers. The cause of the depressurization could not be determined, but it illustrates the need for extreme vigilance to prevent such incidents. Although the records are quite incomplete, one gains the impression that there has been a decreasing danger from the loss of cabin pressure.

The structural integrity of current high altitude jet transports appear to be very reliable. For the most part the incidents in recent years have been concerned with problems of door seals with relatively fewer resulting from failures in compressors, ducts, and controls. In the few instances where cockpit windows have cracked, precautionary descents have been made, with no reports of sudden decompression due to complete loss of windows. Some instances have been reported relating to poor maintenance or improper operation of the equipment.

The British experience in which cabin altitude pressures reached 10,000 feet has closely paralleled that of the American air transport operators. From 1960 through 1967 there were 63 such incidents. Oxygen masks were apparently used in many of these instances. The author has recently had an opportunity to examine the records of cabin pressure malfunction incidents of one of the largest British operating airlines for the calendar year 1970. There was only one case reported in which the oxygen masks were released to the passengers. A large majority of the cases involved smoke or vapors in the cabin arising from compressor oil or blocked valves in the air conditioning system.

V. Implications and Summary

It is relevant to conclude this lecture with a brief interpretation of the success of modern air travel in relation to the development of pressurized cabins. Undoubtedly this design feature has played an important role in the increased volume and safety of this mode of travel.

The number of revenue passengers has gone up between 10 to 15 percent each year since 1951. The total number of persons carried on domestic and international routes combined was approximately 290 million in 1969, and more than 300 million in 1970.

Passenger travel by air between the U.S. and foreign countries is four times as great by air as by sea; on North Atlantic routes there are eleven times more passengers by air than by sea. The airlines in the U.S. are now carrying larger numbers of passengers in inter-city travel (96 million) than the railroads (7.6 million) and the motor buses (25 million). The scheduled airlines of the U.S. fly approximately one-half of the total number of revenue passengers on a world-wide basis, i.e., in 1968, 150 million, and in 1969, 159 million passengers.

The safety record of the scheduled domestic and international air carriers is very favorable. However, there is no meaningful method of comparing the safety records of different forms of transportation because of the lack of a common denominator or baseline. On a world-wide basis, the fatality rate per 100 million passenger miles in 1967 was 0.25. The absolute number of passengers killed on scheduled services was 619 in 1969, and 617 in 1970. The only fatal accident in scheduled service (US) during 1970 occurred on an international flight on December 28, 1970. In domestic operations in the U.S. no fatality occurred on scheduled routes in this year. This safety record appears to be a remarkable one in every respect.

It is interesting to note that jet air travel, especially with pressurized cabins, also has achieved an excellent record in regard to passenger comfort and safety. For the last 20 years the author has attempted to obtain the numbers of in-flight non-accident deaths which have occurred on scheduled air transports. The rate of one passenger death per million revenue passengers has remained approximately the same in spite of the large increase in volume. Undoubtedly the pressurized cabin has contributed to this enviable record.

In tracing the history and development of pressurized cabins, it has been possible to show how this design feature, furthered by the development of jet engines, has been dependent upon many basic investigations relating to human factors and related aeromedical disciplines. There is every reason to believe that additional studies will be necessary to realize the greatest opportunities for this field of travel in the years ahead.

Finally, it seems to the author that those of you in the field of aerospace medicine have made many important contributions to safety in general. In addition, a more favorable climate now exists in regard to research of this type and to the development of more effective health and safety programs. New concepts and new knowledge from the fields of aeronautical engineering, biotechnology, biostatistics, medicine, and psychology, for example, are providing fresh impetus for experimental studies. Also, there is increasing public support and encouragement at higher levels of government for safety research in aviation and other fields of transportation.

TABLE I

Analysis of Cabin Pressurization Based on Safety, Comfort, and Operating Efficiency (1)

Advantages	Disadvantages
Safety	
1. Time in icing layers cut down by more rapid ascents and descents without influencing passengers	1. Possibility of forced descents to lower altitudes in bad weather or over mountainous areas in the event of a loss of pressure
2. Stronger fuselage providing greater safety in forced landings on land or water	2. Necessity for carrying emergency oxygen in the event of a sudden loss of pressure
3. Less fatigue in flight crews	3. Increased distortion of vision through thicker windowpanes
4. Leakproof windshields promoting greater efficiency in pilots	
5. Better birdproofing because of thicker windowpanes	
Comfort	
1. Constant and adequate supply of oxygen	1. Greater difficulty in the control of odors
2. No need for cumbersome masks	2. More limited rates of cabin ventilation
3. No interruption in sleep during rapid descents	3. Possible results of oxygen lack in case of cabin or compressor failure
4. Freedom of movement, conversation, and other activities without oxygen masks	4. Passenger window space reduced unless paid for in excessive weight penalties
5. Decrease in airsickness due to smoother over-the-weather flying	
6. More even cabin temperatures	
7. Less distress to middle ear during rapid rates of ascent and descent	
8. Conservation of moisture in recirculated air	
9. Lowered noise transmission because of thicker windows and heavier structures	
Operating Efficiency	
1. Increased regularity of schedules because of over-the-weather flying	1. Weight penalties around bulkheads, doors, and windows
2. Increased speed at high altitudes due to lower density of air	2. Increased maintenance of supercharger and cabin pressure regulator
3. Per annum payloads increased because of greater regularity of service and use of direct routes	3. Greater maintenance involved in preventing air leaks around the sleeves and bellows for the controls leading in and out of pressurized sections
4. Aerodynamic cleanliness promoted; less drag and fewer leaks	4. Greater difficulty in cooling the cabin at low altitudes
5. Lowered fuel consumption because of less time spent in ascents and descents	5. Added weight of fuel to supply power for superchargers
6. Increased efficiency in temperature control because of heating the air during compression and better sealing of apertures	6. Disposal of water or waste in flight more difficult
7. No human limitations during rapid climbs to cruising altitudes and efficient descents	

TABLE II

INCIDENCE OF DYSBARISM IN SUBJECTS EXPOSED TO DECREASED PRESSURE IN ALTITUDE CHAMBERS

Figures are given in cases per 100 persons exposed.

Symptom	USAF[1] 1954	USAF 1955	Motley[2]	Fulton[3]	Henry[4]
Aerotitis	6.85	8.45	----	----	----
Aero-sinusitis	2.17	2.36	----	----	----
Aero-dontalgia	0.40	0.57	----	----	----
Abdominal Gas Pain	4.23	4.02	----	2.40	----
Bends	2.85	2.63	13.80	16.30	60.00
Chokes	0.04	0.11	0.28	2.80	----
Neurol.	0.05	0.03	0.25	5.00	----
Skin	----	----	1.00	----	----
Collapse	0.65	0.90	----	0.85	----
Total	17.27	19.13	15.33	27.35	60.00

[1]Usually Standard Type III Flight to peak altitude of 45 M'. Duration of flight about 1 - 1 1/2 hrs. with mild to moderate exercise in demonstrations at 25 M' and 35 M'.

[2]Usually a 2 hr. flight with peak altitude of 35 M'.

[3]A 3 hr. flight with peak altitude of 38 M'.

[4]A 1 1/2 hr. flight with peak altitude of 35 M'.

TABLE III

RAPID DECOMPRESSION IN USAF AIRCRAFT

January 1, 1951 - April 1955

Altitude	Total Decomp.	Fighter	Bomber	Loss of Equip.		Injured (Crew Effects)	Loss of Vision (Crew Effects)	Loss of Cons. (Crew Effects)	Cold Effects (Crew Effects)
Unknown	1	1	0	1		0	0	0	0
10-14 m'	14	8	6	0		0	6	1	0
15-19 m'	21	17	4	1		0	2	0	0
20-24 m'	18	16	2	0		3	5	0	1
25-29 m'	12	10	2	1		3	0	0	1
30-34 m'	16	13	3	1		5	0	1	3
35-39 m'	10	8	2	1	O_2 hose sev.	2	0	1	1
40 plus m'	6	3	3	2		2	0	0	0
Total	98	76	22	7		15	13	3	6

Cause of Rapid Decompression *

1. Canopy jettisoned 47

2. Loss of navigator or bombadier's hatch 11

3. Plexiglass disintegration 32

4. Canopy slid open 3

5. Cabin puncture 2

6. Fuselage failure 1

*for the period Jan. 1, 1951 - April 1955

TABLE IV

Year	Total Number of Depressurization Incidents	Incidents at Cruise Altitudes, or above 20,000 Feet: Loss of Pressure Requiring Emergency Descent and Deployment of Oxygen Masks	Incidents at Cruise Altitudes, or above 20,000 Feet: Incipient Loss of Pressure or Pressurization Malfunction, Precautionary Descent	Pressurization Problem During Takeoff and Climb, Flights return to airport
1966	46	16	7	23
1967	58	15	14	29
1968	35	7	14	24
1969	39	9	5	25

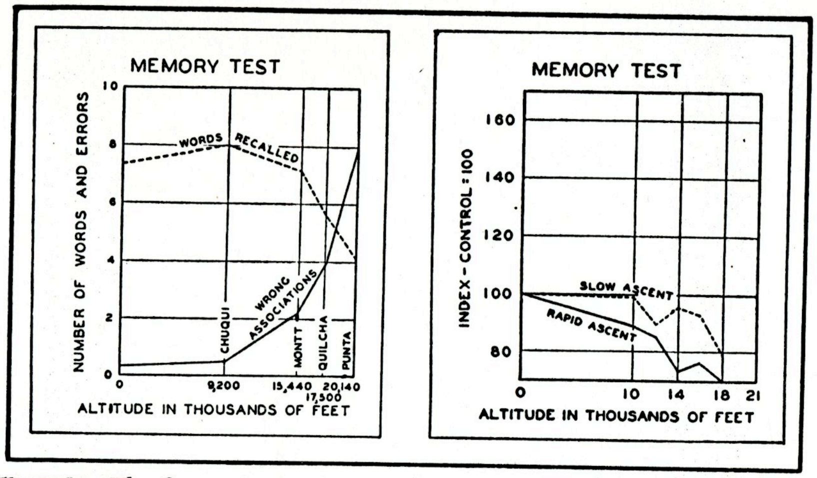

Figure 1. The figure shows the effect of altitude on immediate memory. Impairment in words recalled and wrong associations is very marked above 15, 000 feet in acclimatized subjects on an Andean high altitude expedition (left). There is a significant decrement in objective tests for immediate memory at altitudes of about 10, 000 feet and over during simulated flights (right).

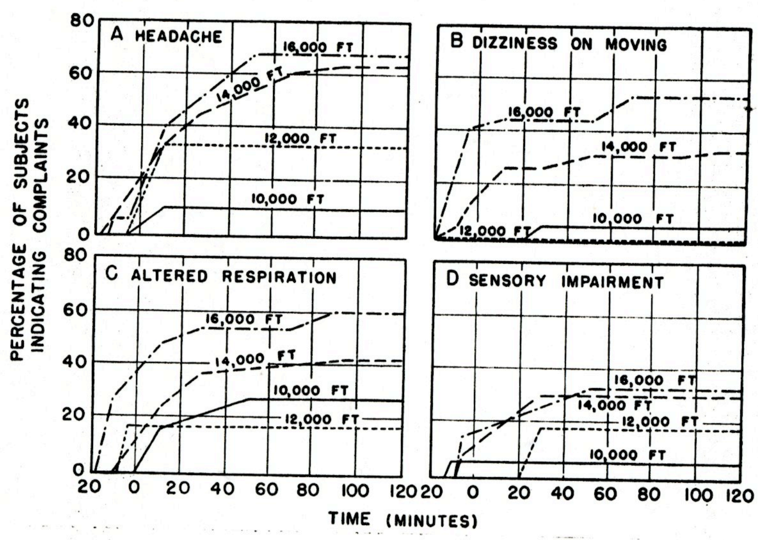

Figure 2. Frequency of complaints at various altitudes and lengths of exposure. The charts show the percentage of subjects voluntarily reporting various complaints during rapid ascents to simulated altitudes and subsequent 2-hr exposures to those altitudes. (1, 16)

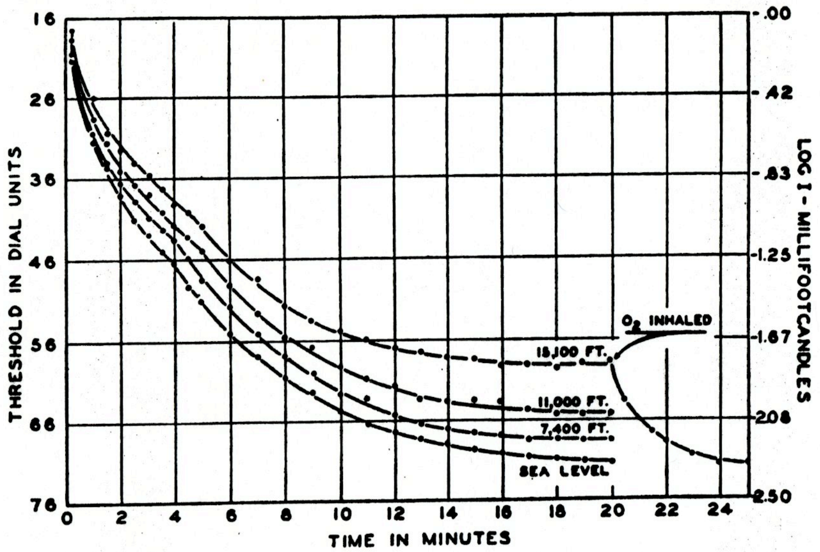

Figure 3. The average light intensity thresholds and dark adaptation curves for 20 subjects during 20 minutes at sea level and at simulated altitudes of 7,400, 11,000, and 15,100 feet. Note the recovery of sensitivity upon inhaling oxygen. (18)

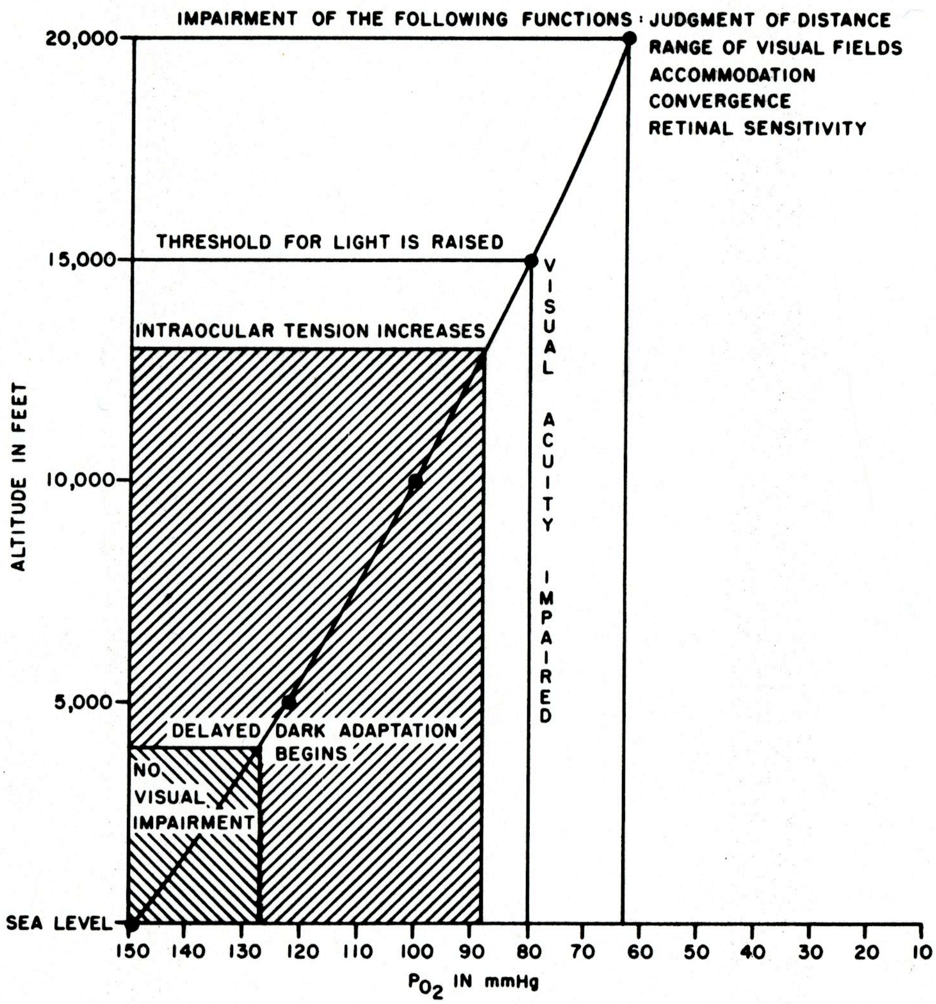

Figure 4. The degree of impairment in four visual functions in relation to altitude and partial pressure of oxygen. Although impairment is indicated in all of the functions shown, it is apparent from the figure that the most sensitive test is that of light sensitivity, or dark adaptation. (13, 20)

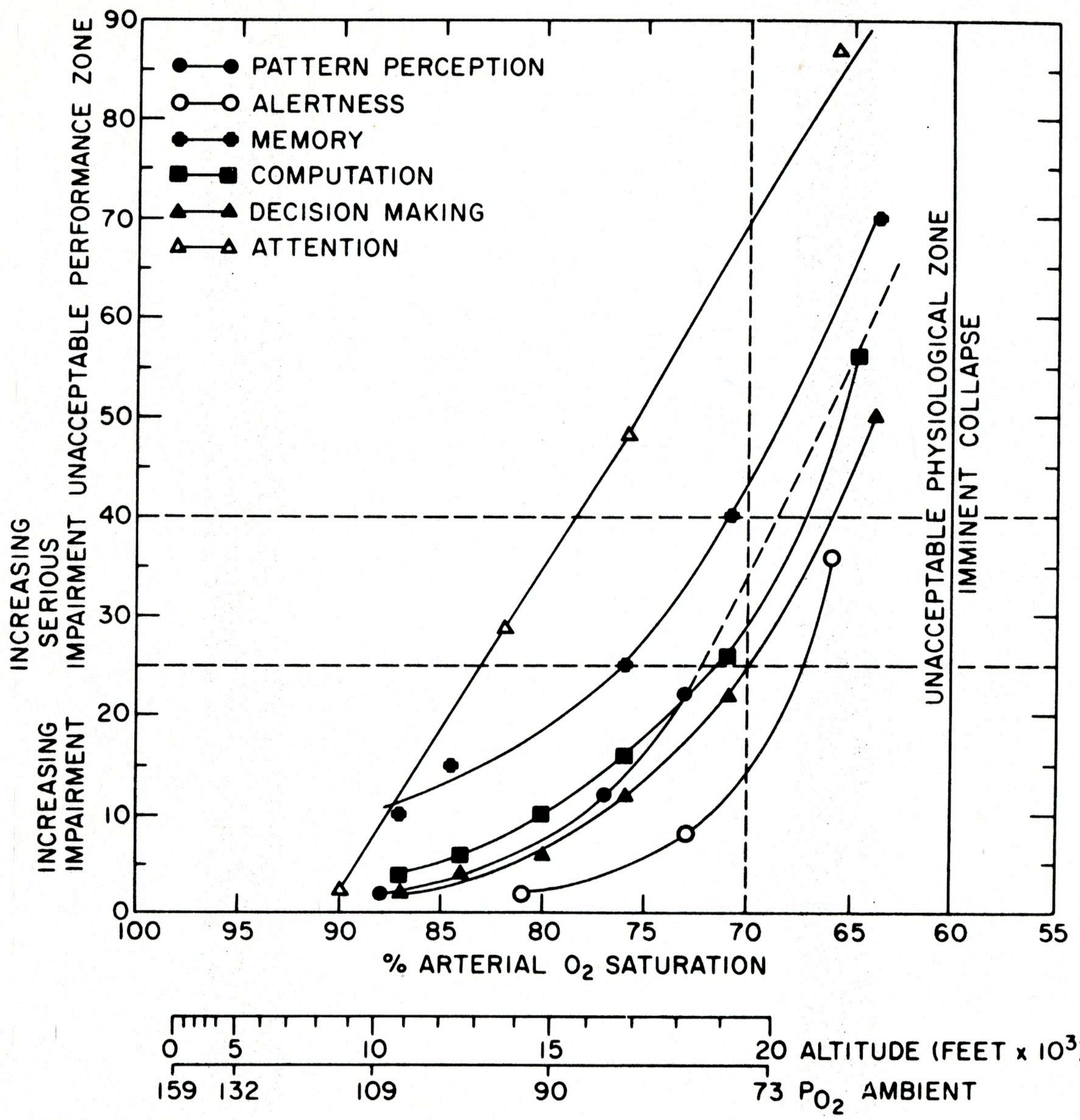

Figure 5. The effects of altitude on memory and other cognitive functions. The figure summarizes the results from studies in which different types of cognitive tests were given at the altitudes indicated. (13, 19, 20)

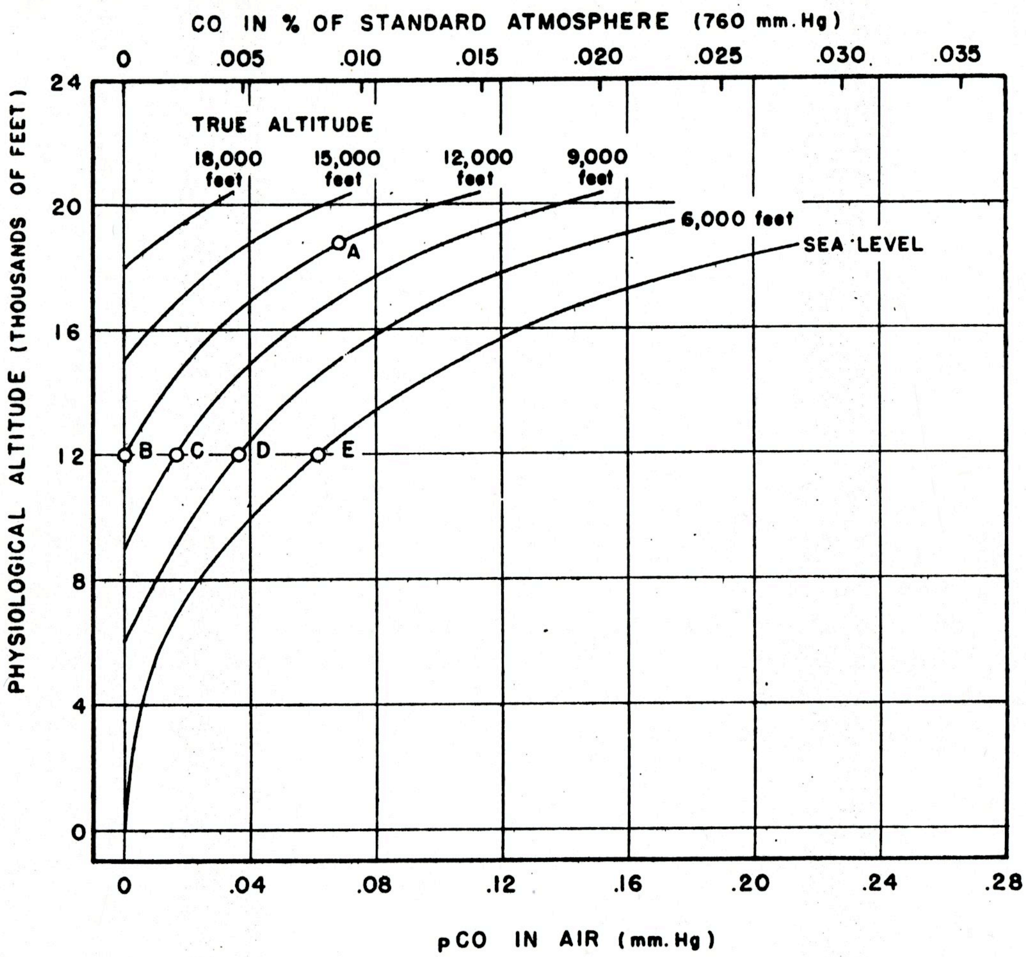

Figure 6. The relation between physiological altitude and the partial pressure of carbon monoxide in air at various true altitudes when equilibrium with the blood has been reached. The figure shows the combined effects of altitude and carbon monoxide as from cigarette smoking. The curves indicate the additive effects of carboxyhemoglobin and altitude hypoxia. Thus, the "physiological altitude" of a person with .005 percent carbon monoxide in the air at an altitude of 6,000 feet would be increased to that normally resulting from an altitude of about 12,000 feet. (22)

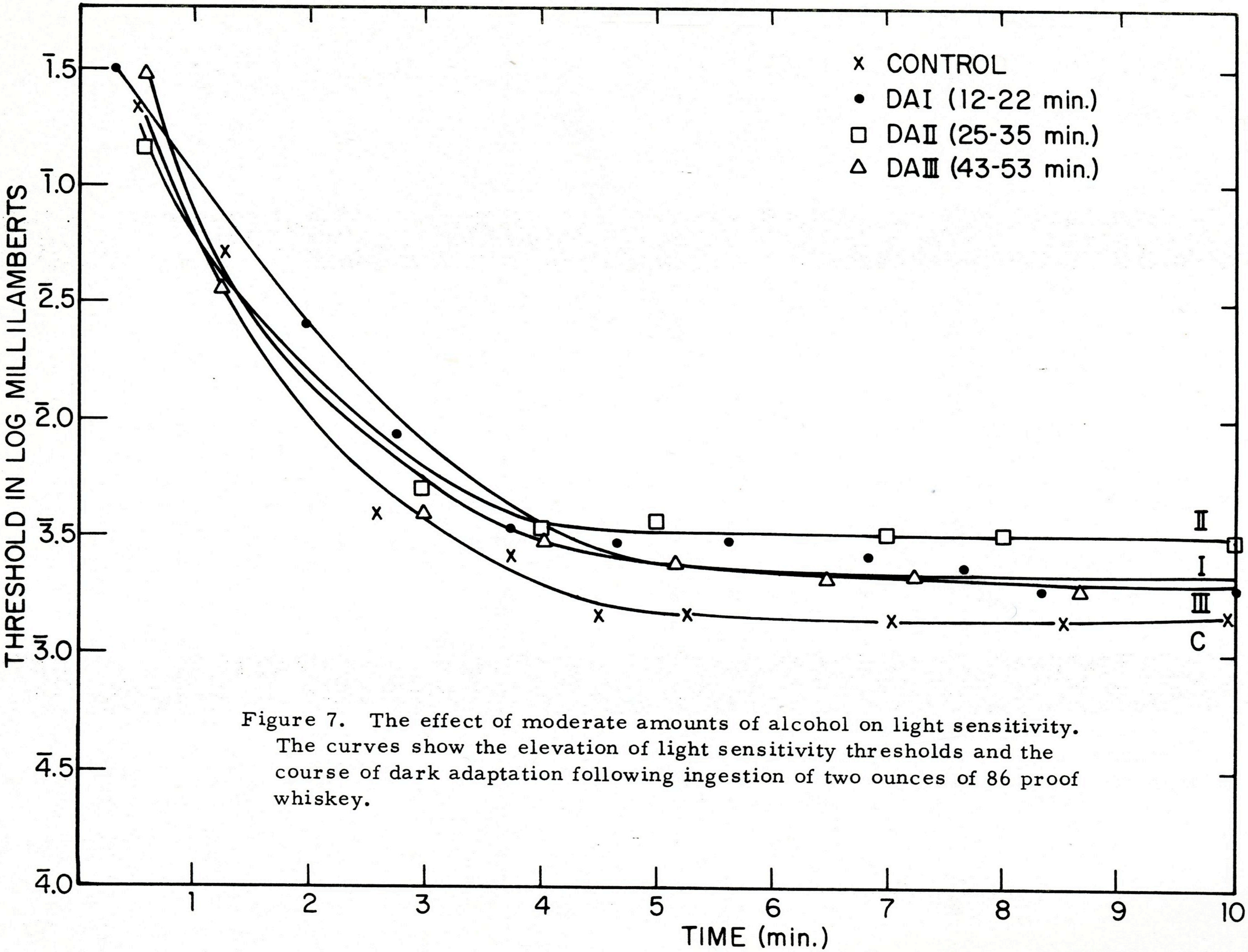

Figure 7. The effect of moderate amounts of alcohol on light sensitivity. The curves show the elevation of light sensitivity thresholds and the course of dark adaptation following ingestion of two ounces of 86 proof whiskey.

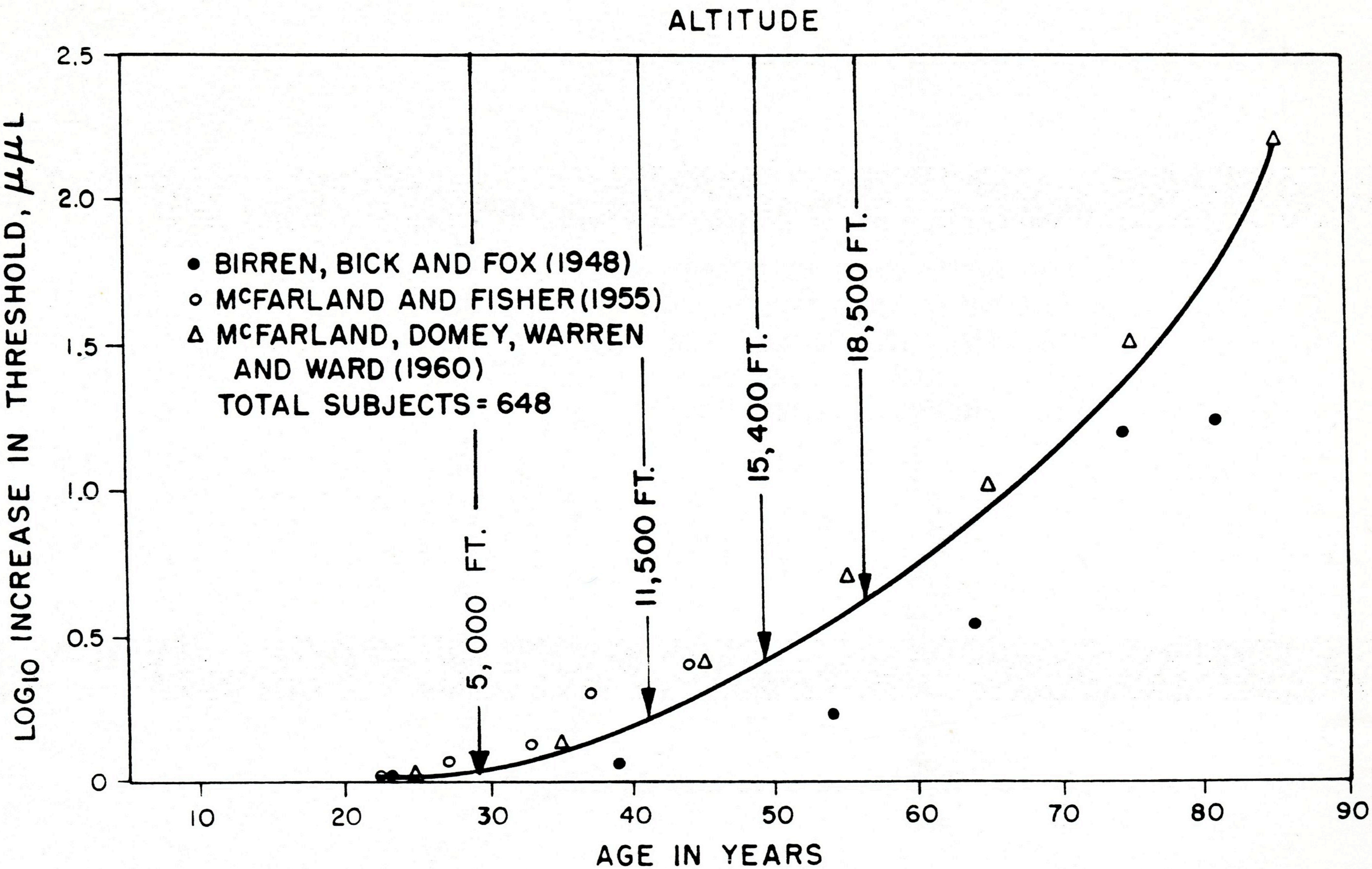

Figure 8. The influence of age on dark adaptation, shown in relation to average values for the influence of altitude on dark adaptation. (24)

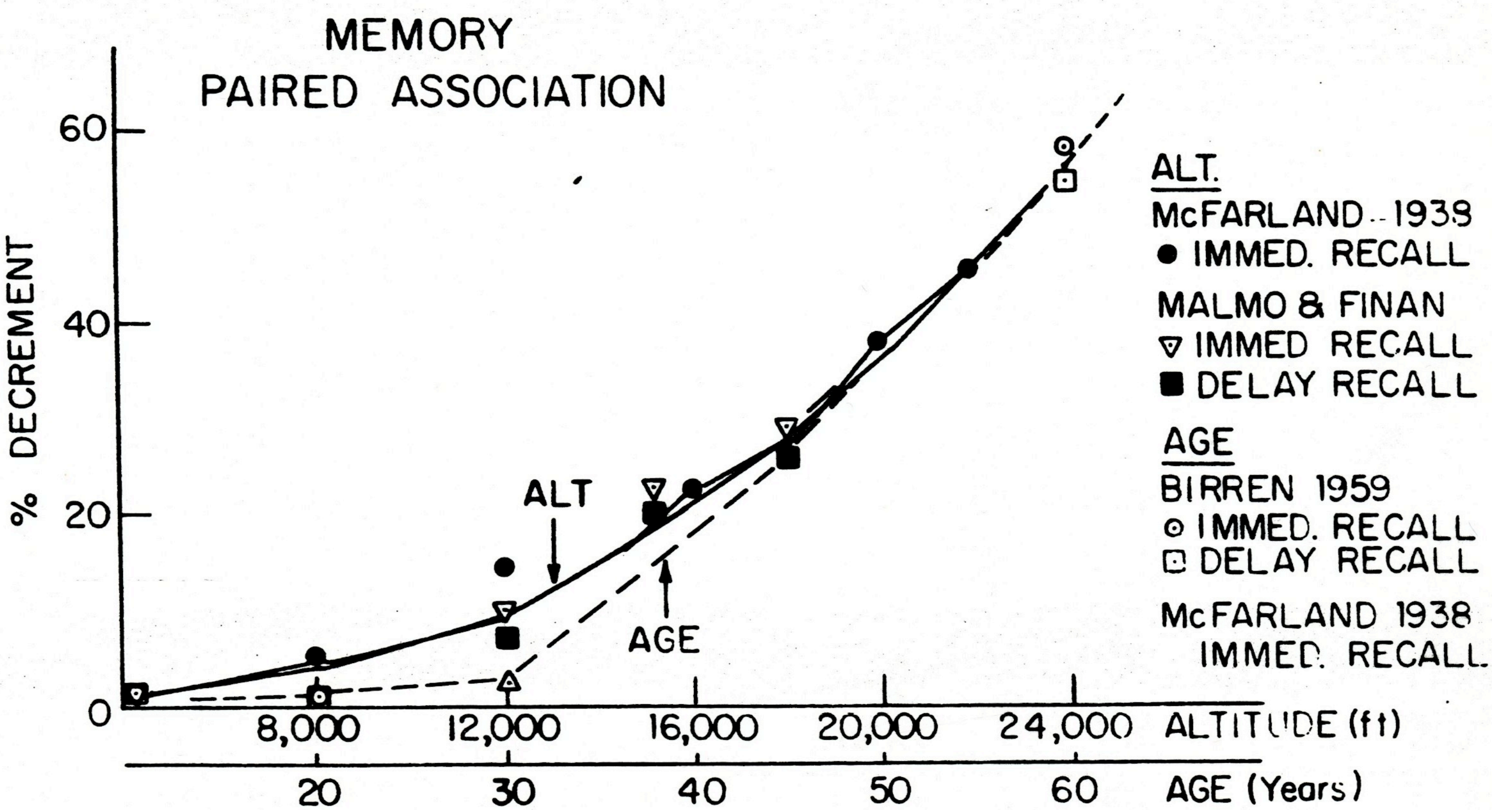

Figure 9. The effects of altitude and aging on selected tests of memory. (24)

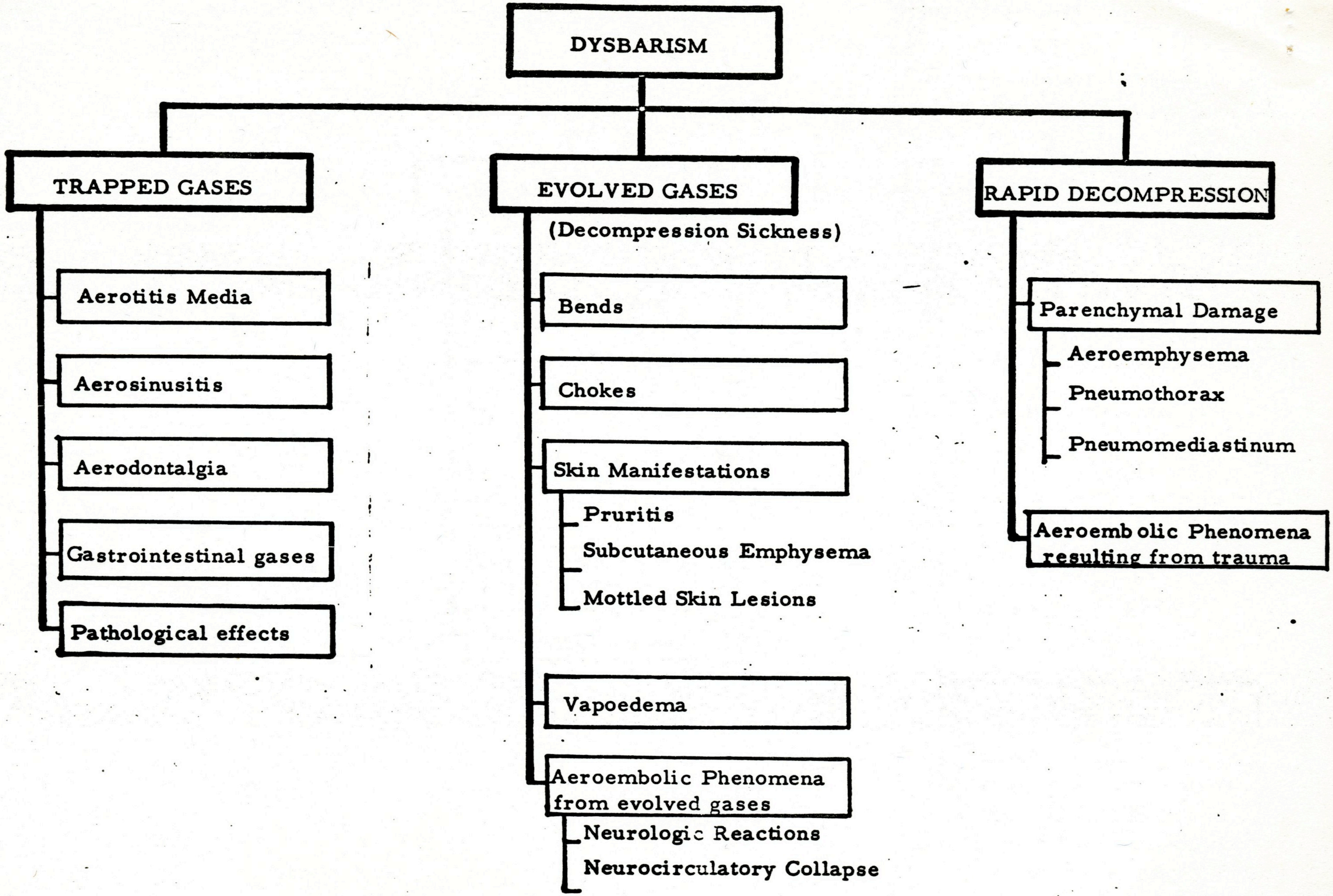

Figure 10. Dysbarism. The diagram indicates the problems resulting from the influence of pressure changes resulting from the expansion of internal gases. The symptoms are classified according to gases trapped in body cavities, evolved gases, or in response to rapid decompression. (28)

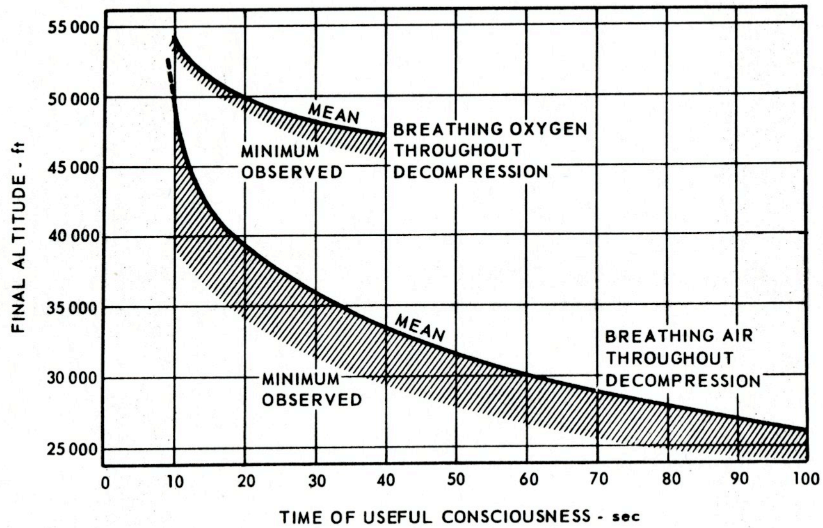

Figure 11. This figure indicates minimum and average duration of useful consciousness in human subjects following rapid decompression breathing air (lower curve) and oxygen (upper curve). At altitudes above 20,000 to 23,000 feet, unacclimatized subjects breathing air will lose consciousness after a variable period of time. Individual susceptibility varies widely except at the highest altitudes. (33)

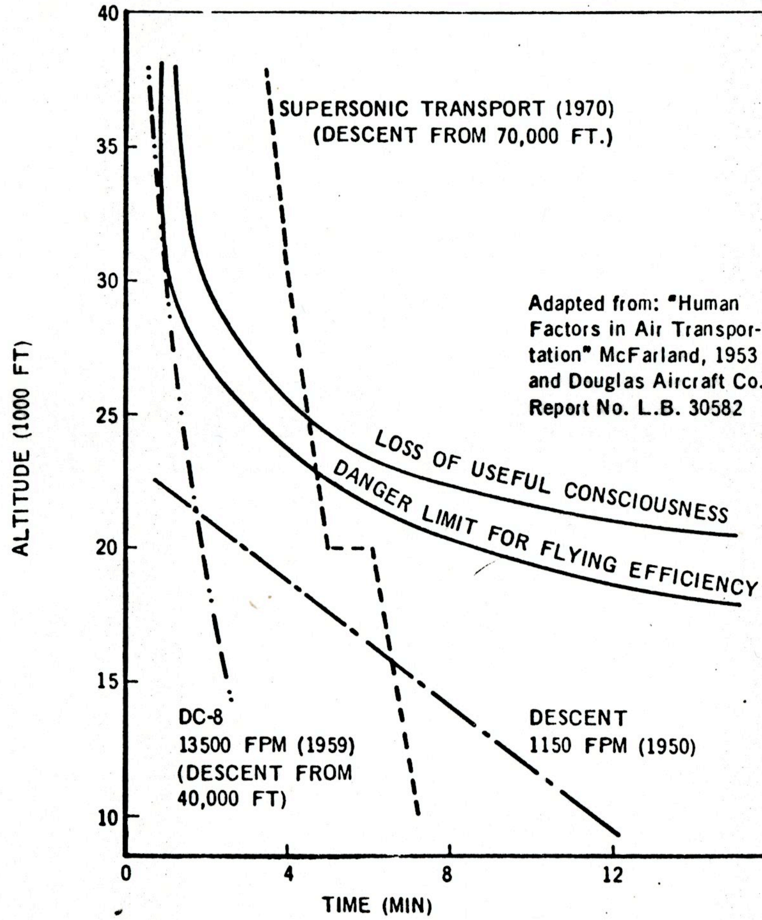

Figure 12. Suggested paths of descent following loss of pressure at high altitude. The curves indicate flight paths of descent in relation to human tolerance limits. (Adapted from 13)

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