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PHYSIOLOGICALLY TOLERABLE DECOMPRESSION PROFILES FOR SUPERSONIC TRANSPORT TYPE CERTIFICATION

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1. Physiologic Boundaries

The life-scientist must provide the aircraft design and systems engineer with guidelines regarding occupant physiologic tolerances to pressurization losses. The guidelines are conveniently expressed in terms of cabin altitude (Y axis) versus time (X axis), and must be based on human tolerances, even though the monkey is reported to survive a decompression to near vacuum without serious illness, if denitrogenated, and if recompression occurs rapidly.[1]

On May 1, 1966, a U.S. parachutist attempting to break the World's altitude jumping record over South Dakota, lost pressure during the balloon ascent at 57,000 feet (apparently by face plate seal opening) and was able to enunciate what apparently was "visor" and then "emergency" during the decompression (the ground tape picked up the noise of apparent helmet decompression to ambient followed by immediate suit decompression.)[2] The chutist, Mr. Nicholas Piantanida, was denitrogenated for about two hours prior to the ascent, and twenty-four seconds after his initial cry at 57,000 feet (62 millimeters of mercury atmospheric pressure) the balloon gondola was cut loose electronically from the ground. The gondola free-fell and then floated by parachute to 40,000 feet in three minutes, where the parachute fully opened and descended the gondola to the ground 25 minutes after it was cut loose. The profile would be as follows:

Time	*Event*
0	Clicking sound, possibly the suit regulator
3 seconds	Piantanida: "visor"
7 seconds	Person on ground: "What did Nick say?" Ground control: "repeat"
12 seconds	Piantanida: "emergency" (The ground control cut the gondola free electronically)
24 seconds	Ground control: "He is free"

Altitude	Millimeters of Mercury	Time From When Cut Free	Remarks
57,000 feet	62	00 minutes	Pressure suit face plate seal apparently gives way
40,000 feet	141	03 minutes	Gondola descent chute partially open, remainder of descent is by parachute
1,328 feet	723	25 minutes	Ground level

Mr. Piantanida was gasping when he was reached and never recovered consciousness, but lived from May 1, 1966 to August 29, 1966, through intensive care and clinical support, including hyperbaric therapy in Minneapolis. Additional treatment and study was performed at the National Institutes of Health, Bethesda, Maryland, when it was felt that through severe hypoxia, permanent damage to critical central nervous system tissue occurred. Even with the period of denitrogenation prior to ascent, some nitrogen embolism could also have occurred.

A crucial factor in the above is that recompression took place slowly, in the absence of supplemental oxygen, at altitudes well above 8,000 feet, seriously compromising the reoxygenation of the oxygen-depleted brain cortex through the intermediate compartments of the lungs and blood.

It is evident that flight above the 40,000 to 50,000 foot levels requires carefully determined precautions with respect to (1) preventing pressurization malfunctions and (2) providing appropriate occupant protection in the event of pressure loss, the type of protection being dependent upon the extent of depressurization, and involving supplemental oxygen and descent procedures. It will become clear that oxygen mask features, donning times and passenger response will be significant factors, as will the cabin attendants' responses. Additionally, the cabin environmental system compressor capabilities and the descent limitations of the aircraft will be vital factors.

For SST prototype flights above 45,000 feet, it may be desirable for the aircrew to wear some type of automatic partial-pressure suit to enable temporary survival in the event of an inadvertent extreme altitude decompression.

2. Physiologic End-points

It is recognized that an infinite series of cabin altitude versus time profiles are physically possible between 8,000 feet (where the depressurization is considered to begin) and the maximum cruising altitude of the SST. Therefore, selected critical cabin altitudes for civil aviation planning are utilized. These are selected on the basis of "physiological end-points", and these are 8,000 feet, 12,000 feet, 14,000 feet, 15,000 feet, 25,000 feet, 34,000 feet, 37,000 feet and 45,000 feet.

The physiological significance of these "end-point" altitudes is as follows:

8,000 feet: The cabin altitude providing a blood oxygen saturation of approximately 93% in the resting individual who does not suffer from an advanced cardiovascular or pulmonary disease. After suffering a hypoxic experience, this is the ceiling of the altitudes to which an individual should be returned for physiological compensatory mechanisms to effectively reoxygenate the body. Operationally, this is why this altitude has been prescribed in Part 121.331 of the Federal Aviation Regulations as the altitude above which passenger oxygen must be available in specified amounts.

10,000 feet: The cabin altitude providing a blood oxygen saturation of approximately 89%. After a period of time at this level, the more complex cerebral functions such as making mathematical computations begin to suffer and night vision is markedly impaired. This is why under Part 121, flight crewmembers must use oxygen when the cabin pressure altitudes exceed 10,000 feet.

12,000 feet: The blood oxygen saturation falls to approximately 87% and in addition to some arithmetical computation difficulties, short-term memory begins to be impaired and errors of omission increase with extended exposure. Part 21 requires that oxygen must be used by each crewmember on flight duty and provided for each other crewmember during the flight when the cabin altitude is above 12,000 feet in consideration of these physiologic findings.

14,000 feet: The blood oxygen saturation is approximately 83% and all persons are impaired to a greater or lesser extent with respect to mental function, including intellectual and emotional alterations. Part 121.333 requires that at a 14,000 foot cabin altitude, oxygen be provided for at least ten percent of the passengers, in recognition of the marginal physiologic aspects of this altitude and the decompensations experienced by a variable proportion of the general population.

15,000 feet: This altitude gives a blood oxygen saturation of approximately 80% and all persons are impaired, some seriously. Recognizing this, Part 121.329 provides that oxygen be available for 30% of the passengers between a 14,000 and 15,000 foot cabin altitude. Above a 15,000 foot cabin altitude, oxygen must be available for all passengers, since all persons are seriously impaired beyond 15,000 feet.

20,000 feet: The blood oxygen saturation is 65% and all unacclimatized persons become torpid, increase in stuporousness, and lose useful consciousness in ten minutes (TUC, the time of useful consciousness, is determined generally from the time breathing oxygen is lost from the respiratory tract with reference to an initial safe level to the time when purposeful activity, such as the ability to don an oxygen mask, is lost.) At 20,000 feet, the TUC is ten minutes. (It should be emphasized here that a given volume of gas at sea level doubles in volume when the pressure is dropped to approximately 18,000 feet).

25,000 feet: This altitude, and all those above it, produces a blood oxygen saturation below 60% and a TUC of 2.5 minutes or less. Above this altitude, the occurrence of bends (nitrogen embolism) begins to be a threat.

30,000 feet: The TUC is approximately thirty seconds.

34,000 feet: The TUC is approximately twenty-two seconds. Provision of 100% oxygen will produce a 95% blood oxygen saturation (at 33,000 feet, a given volume of gas at sea level will have approximately quadrupled).

37,000 feet: The TUC is approximately eighteen seconds. Provision of 100% oxygen will produce approximately an 89% oxygen saturation. As this altitude is exceeded, the oxygen begins to leave the blood unless positive-pressure oxygen is supplied. (It is emphasized here that a given volume of gas approximately quintuples when the altitude changes from sea level to 38,000 feet.)

45,000 feet: The TUC is approximately fifteen seconds and positive-pressure oxygen is of decreasing practicality due to the increasing inability to exhale against the oxygen pressure.

3. Physiologic End-points and Occupant Duties

The Federal Aviation Regulations recognize that as cabin altitude increases, there is a progressive loss of oxygen pressure and that this loss must be given the appropriate attention in airworthiness design and operational regulations.

A comprehensive table of pressure, altitude and related parameters is as follows (the data will vary slightly from that given in the table depending upon atmospheric fluctuations and pertain to conditions approximating a standard atmosphere):

I	II	III	IV
Pressure Altitude (Feet)	Atmospheric Pressure (Millimeters of Mercury)	O^2 Partial Pressure (20% of Table II in Millimeters of Mercury)	Percent Arterial O^2 Saturation Without SupplementalO^2
80,000	21	4	Below 60
70,000	34	7	Below 60
60,000	54	11	Below 60
50,000	87	17	Below 60
40,000	141	30	Below 60
37,500	159	33	Below 60
35,000	179	38	Below 60
32,500	201	42	Below 60
30,000	226	47	Below 60
27,500	252	53	Below 60
25,000	282	60	Below 60*
22,500	314	66	60
20,000	349	73	65
16,500	403	85	77
14,000	446	94	83
12,500	474	100	87
10,000	523	110	89
7,500	575	121	93
5,000	632	133	95
2,500	694	147	95
0	760	160	96

The concomitant approximate times of useful consciousness are as follows:

Altitude	TUC
40,000 feet	15 seconds
35,000 feet	20 seconds
30,000 feet	30 seconds
28,000 feet	1 minute
26,000 feet	2 minutes
24,000 feet	3 minutes
22,000 feet	6 minutes
20,000 feet	10 minutes

The rapid reduction in TUC between 20,000 feet and 28,000 feet reflects the increasingly ineffective respiratory, blood and cellular compensatory mechanisms utilized to combat hypoxia.

There are three critical physiologic compartments which communicate with one another with respect to oxygen transmission. These are the central nervous system tissue, the blood and the pulmonary system. The latter system communicates with the gaseous environment which is made up for our purposes of (1) the pressure vessel, *per se*, which in the case of the SST is not hermetically sealed, but communicates with (2) the outside atmosphere.

The living occupant cannot be totally divorced from his physiologically communicating environment, hence the life scientist will prescribe differing safety standards in cases where an individual is surrounded by a relatively nonhazardous environment as opposed to the circumstances where the surrounding environment is potentially hazardous. In extreme environments, the safety standards will be considerably extended. The above principle is reflected in FAR Part 121.331 which requires no more than 10% of the passengers necessarily be provided with oxygen if the flight is not to exceed 25,000 feet and if a descent along the route can safely be made to 14,000 feet in less than four minutes. If the flight cannot descend to 14,000 feet within four minutes, 100% of the passengers must be provided oxygen for that portion of time above 15,000 feet. This well established philosophy will be applied in consideration of SST regulations.

Another physiologic consideration is that following exposure to a hypoxic altitude where the pulmonary system is exhausted to a low oxygen

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* A blood arterial O_2 saturation below 60% leads to rapid collapse. 77% is accompanied by considerable handicap and 84% produces appreciable handicap. 90% saturation presents no detectable hypoxia in most persons with the exception of some night vision impairment.

tension, the blood oxygen tension is then lowered, followed by a loss of oxygen from the body tissues, an especially critical circumstance for the central nervous system tissue which has no alternative metabolic pathway capable of functioning in the absence of oxygen (an "anaerobic" system) as some other tissues contain. Recompression to an 8,000 foot cabin altitude should enable a progressive reoxygenation to safe levels, beginning first with the pulmonary compartment, then, successively, the blood compartment and, ultimately, the central nervous system tissue compartment. The provision of supplemental breathing oxygen during the above process will hasten central nervous system reoxygenation.

In determining physiologic end-points, a chamber decompression experience at the U.S. Air Force School of Aviation Medicine, Randolph Air Force Base, 1952, is of interest. The twenty-five year old subject* was decompressed from 10,000 feet to 32,000 feet in approximately two seconds (explosively). An A14A mask and a pressure demand D2 regulator were utilized. The latter, which allowed respiration with the ambient up through 10,000 feet, was inadvertently not switched to automatic, with the result that after achieving 32,000 feet, the subject, whose lungs were essentially evacuated of gaseous content, could not inhale since the valve communicating to the ambient atmosphere was closed by an aneroid. The subject remained conscious about fifteen seconds and rapidly collapsed, becoming intensely cyanotic (bluish discoloration due to low oxygen saturation of the blood). The decompression from the 10,000 foot ambient resulted in lung evacuation to oxygen levels below those of venous blood (the latter being 35–40 mm mercury oxygen pressure), with the result that oxygen flowed from the blood to the lungs.[6]

The main chamber valve was immediately opened (within one minute) and the chamber was returned to ground level in less than a minute's time. The subject was gasping and remained unconscious for thirty minutes, and gradually regained consciousness, passing through a stage of confusion and disorientation lasting about fifteen minutes. One hour after the return to ground level, the subject still had certain sequellae, including a coordinative inability to button his trousers and shirt or to tie his necktie. After sleeping for three hours, he awoke fully recovered and no detectable sequellae existed. No ear difficulties accompanied recompression.

The relatively shorter time of consciousness following an "explosive" decompression which is compounded by the inability to inhale, results from oxygen transfer from the blood to the evacuated lungs, and illustrates the rapidity of oxygen transport between the pulmonary and blood systems, followed by an equally rapid passage of oxygen from the central nervous system to the blood. At the 25,000 foot and above levels, oxygen lack is the number one critical consideration in physiologic requirements.

4. Occupant Physiologic Variation

Much of the altitude tolerance data in the scientific literature has been obtained in detailed military studies, utilizing a relatively young, adult male population, consisting of men who have passed the physical standards set by the military services.

If a 1.0 to 1.1 figure is assumed for the military population variation, a 1.3 figure is assumed for civil passenger population variation. In other words, it is anticipated that up to approximately 30% of the civilian passengers may be troubled sufficiently to require oxygen at cabin altitudes falling between 14,000 and 15,000 feet (see FAR, Part 121.329(c)(2)).

Obviously, in view of wide individual health and physical status variations, no hard and fast criteria can be stated which encompass all SST passenger altitude tolerance capabilities. Such conditions as pulmonary emphysema, anemias, cardiovascular, cerebrovascular and pulmonary disease will exist to a variable extent in any complement of civilian passengers. Any increase in age of the adults will heighten the spread from normality to abnormality found in a given passenger population.

For the above reasons, in order that assurance is given that the majority (95%+) of airline passengers, as we know them today, receive adequate environmental protection, medical judgmental considerations by aerospace medical specialists must enter in determining how safe or unsafe a given depressurization profile is for a typical passenger cohort. Accordingly, a degree of conservatism is invoked with regard to constructing SST decompression profiles. In arriving at these judgments, it may be helpful to refer to FAR 121.291, which describes a rep-

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* The author

resentative civilian passenger population with respect to age and sex distribution. This provides for 5% of the persons to be in excess of age sixty. At least thirty percent are females and 5 to 10% are children under 12 years of age, prorated. Three infants, two years and younger, also are considered in the representative airline passenger population.

5. Application of Physiologic Information in Type Certification (Part 25 of the Federal Aviation Regulations)

In the United States, type certification under Part 25 (air carrier airworthiness) of the Federal Aviation Regulations involves demonstrations in which a specific aircraft is shown to be capable of complying with certain prescribed performance data. Since various airlines acquiring the aircraft differ in the nature of their operations, another portion of the FAR's covers various operationally safe limits (see, for example, Part 121 regarding domestic and flag air carrier operations).

The Tentative Airworthiness Standards to which this paper is primarily addressed, are those applicable to Part 25. Necessarily, the altitude-time profiles for required demonstration under Part 25, are more stringent than may be allowed under an operational part of the FAR's. For example, it may be deemed necessary to demonstrate under Part 25 a capability of cabin recompression to 8,000 feet within ten minutes following a pressure loss to a given altitude, simply to insure the cabin integrity and system capability of the aircraft. However, if later, under the operating regulations, a depressurization emergency should occur which would prevent a repressurization of the cabin to 8,000 feet, a somewhat higher cabin altitude might be permitted if it can be shown that: (1) Operational considerations demanded the higher cabin altitude following the emergency, and (2) an adequate level of physiological safety could be provided at the higher cabin altitude.

For SST FAR 25 type certification considerations, the cabin pressure loss is considered to begin at an 8,000 foot cabin altitude. The pressure profile will (1) follow an ascent curve which may vary from an infinitely steep upward slope (worst case) to a more gradually increasing slope, (2) have a specific "dwell time" at a given higher altitude, and (3) follow a descent curve which allows repressurization such that the entire sequence of pressure loss, dwell and repressurization, will return the cabin altitude to 8,000 feet within ten minutes.

The Federal Aviation Act of 1958 provides that the Administrator's duty is to promote safety of flight in civil aircraft in air commerce by prescribing minimum standards governing the design, materials, workmanship, construction and performance of aircraft in the interest of safety plus minimum standards governing appliances, as may be required in the interest of safety. At the same time, the Act provides that the Administrator, in issuing certificates, shall give full consideration to the duty of air carriers to perform their services with the highest possible degree of safety in the public interest.[5] Accordingly, in preparing environmental standards for SST type certification under Part 25, attention will be given to supporting both of the above requirements to the extent possible, compatible with physiologic tolerances and technologic achievement.

It is noted that the "price" for advancing to ever more extreme environmental circumstances, is necessarily a more adequate protection of vehicle occupants.

It has been suggested that in line with the improved automation of the SST to remove crew workload, an on-board cabin altitude recording barograph be placed on each SST, the record to begin at times when the cabin altitude exceeds 8,000 feet and to end when the altitude returns to 8,000 feet. Such devices are relatively inexpensive and would do much to provide valuable pressure data to maintenance personnel in the event of a pressure system malfunction, not to mention the aeromedical persons who are responsible for the welfare of the passengers.

Air transports have averaged about 54,000 flight hours between pressurization malfunctions.[8] In view of the more extreme pressure differential between the SST cabin and the outside atmosphere, more demands will be placed upon the pressure vessel and equipment, including the compressors. It is possible, although deemed remote, that SSTs will be subject to pressurization malfunctions although less often than found in older subsonic jet aircraft (due to improved technology). We must, then, plan to preclude such eventualities, insofar as possible, and to provide appropriate protection should such occurrences arise. It is noted that complete decompressions to cruising altitude levels will be so extremely remote that the probability is less than that for complete wing loss.

6. SST Tentative Airworthiness Standards, Part 25, December 29, 1967

These standards were evolved to delimit human physiologic tolerances with respect to hypobarism. Hypoxia (oxygen deficiency) and nitrogen embolism (bends) are primary aspects. In developing these standards, the rationale is described in the FAUSST VI Working Paper.[3]

The following profiles were prescribed:

Limit I (no passenger oxygen)—Nine minutes at 15,000 feet with a return to 8,000 feet in the tenth minute.

Limit II (passenger oxygen for all)—Seven minutes at 25,000 feet, with a return to Limit I in the eighth minute, and 8,000 feet in the tenth minute.

Limit III (oxygen for 10% of the passengers)—Two minutes at 25,000 feet, with a return to Limit I in the fourth minute, with a return to 8,000 feet in the ninth minute.

Limit IV (Ultimate Survival Condition/passenger oxygen for all)—One minute at 37,000 feet, with a return to Limit II in the second minute, with a return to Limit I in the eighth minute, and a return to 8,000 feet in the tenth minute.

In developing the above curves, no data were available regarding SST ascent profiles, therefore the "worst-case" depressurizations were used, that is, instantaneous. To do otherwise would have necessitated speculation.

Additionally, it was assumed that with the exception of the Limit I and III curves, oxygen is available to all passengers, but that some persons may become hypoxic during the various emergencies. Therefore, times were selected which were considered not permanently damaging to this latter group.

It was recognized when these curves were developed that the ascent aspect would ultimately have to be addressed, and that the above times were tentative. It was also recognized that further considerations and expert medical opinion would very likely lead to some modifications of these profiles. The latest status on the profiles are reported in the Tentative Airworthiness Standards for the SST, 1 January 1970.

It is also inherent in the conservativeness of these profiles, that their conservative nature is justified by virtue of the SST cruising altitudes which will be up to twice those of subsonic jet transports. The latter, in effect, are already "half way down" from higher outside ambient pressure levels and have, thereby, a significant descent-time lead over supersonically cruising SST's which must slow to a subsonic speed at some point in establishing a finite descent rate from a considerably higher altitude.

7. BAC/SUD Comments on SST Tentative Airworthiness Standards

On September 30, 1968, representatives of SUD Aviation commented that the December 29, 1967, SST Tentative Airworthiness Standards for Part 25, were more detailed than those of the December 30, 1966, version, the latter calling for a cabin altitude exceeding 15,000 feet temporarily but never exceeding 40,000 feet. The term "temporarily" was interpreted as a cabin altitude-time history which at no point exceeds the curve of a ten minute uniform descent from 40,000 feet to 15,000 feet.

The December 29, 1967, cabin altitude-time curves provided in the Tentative SST Airworthiness Standards were reviewed by BAC/SUD personnel and a theoretical analysis was made regarding a cabin altitude-time history for the "most critical failure".

The BAC/SUD analysis shows that a theoretical Concorde cabin decompression profile for a most critical failure would be as follows (starting at 8,000 feet and returning to 10,000 feet cabin altitude):

Time	Cabin Altitude
30 seconds	25,000 feet
1 minute	35,000 feet
2 minutes	32,000 feet
3 minutes	31,000 feet
4 minutes	30,000 feet
5 minutes	25,000 feet
6 minutes	20,000 feet
7 minutes	7,000 feet
8 minutes	14,000 feet
9 minutes	11,000 feet
10 minutes	10,000 feet

With respect to the above data, it is observed that the profile presents a moderately rapid cabin altitude ascent to 35,000 feet (within one minute), a post 35,000 foot dwell time above 30,000 feet of three minutes, and a rather slow descent to 10,000 feet over the remaining six minutes.

Assuming 100% use of oxygen by the passengers, *hypoxia* should be alleviated. The Concorde cabin altitude profile peaks at a lower limit (35,000 feet) than the 37,000 foot limit prescribed by the 1967 tentative SST standards. By way of a trade, in the above theoretical consideration, the Concorde dwell-time after arriving at 35,000 feet is three minutes, whereupon the 30,000 foot level is achieved, whereas the December 1967 SST standard called for a return to 25,000 feet after one minute at 37,000 feet, with passage of the 30,000 cabin altitude foot level 30 seconds after the descent began.

By way of another trade, cabin altitude at five minutes after decompression is calculated to be below that allowed in the December 1967 tentative SST standards, and remains below until the tenth minute where the Concorde profile levels at 10,000 feet. These Concorde profiles are theoretical and will undoubtedly undergo further modifications with time.

It is felt that some logical trade-offs in altitude-time profiles can be made, assuming the 100% availability and use of passenger oxygen, which enable a profile to remain within the range of human tolerance. It is also felt that the cabin altitude for certification purposes under Part 25 should return to 8,000 feet to allow proper re-oxygenation of persons who may have inadvertently become hypoxic during the experience, possibly through misuse of their masks.

With respect to the longer dwell times above 30,000 feet, there is a finite increase in the probability of nitrogen embolism evolution, a factor which discourages trade-offs in lengthening such times.

8. Boeing Company Suggestions for SST Airworthiness Standards

On November 22, 1968, the Boeing Company presented to the FAA the following proposal for an updated tentative FAR 25.841(a) for SST pressurization:

> "(1) If Certification for operation over 50,000 feet is requested the following times must comply with those shown in Table I for the following conditions:
>
> (i) Any double failure in the pressurization system, or
>
> (ii) Any single failure in the pressurization system combined with (a) a 12-inch long skin puncture, or (b) a complete loss of a door seal element.
>
> (2) Maximum cabin pressure altitude and cabin pressure altitude exposure times must comply with those shown in either Table I or Table II for the following conditions:
>
> (i) Complete loss of a typical skin panel as bounded by the crack stopper pattern, unless it is shown by tests that the maximum opening resulting from crack propagation is less than that of the panel.
>
> (ii) Complete loss of cabin window.
>
> (iii) Penetration by a large segment of an engine turbine or compressor disc unless it is shown that engine disintegration will not result in a puncture of the pressure vessel.
>
> (iv) The maximum opening resulting from damage based on a rational analysis, on experience and on tests of the configuration under consideration."

TABLE I.—(Boeing Proposal)

	A. Cabin Altitude may not Exceed 15,000 feet, Assuming No Passenger Supplemental Oxygen may be present	B. Cabin Altitude may Exceed 25,000 feet, Assuming Passenger Supplemental Oxygen is present
Allowable Exposure Time at the Following Cabin Altitudes:		
Above 18,500 feet	Inapplicable	15 minutes
Above 15,000 feet	Inapplicable	30 minutes
Above 10,000 feet	15 minutes	No Time Limit

TABLE II.—(Boeing Proposal)

	A. Cabin Altitude may not Exceed 25,000 feet, Assuming No Passenger Supplemental Oxygen may be present	B. Cabin Altitude may not Exceed 37,000 feet, Assuming Passenger Supplemental Oxygen is present
Allowable Exposure Time at the Following Cabin Altitudes:		
Above 35,000 feet	Inapplicable	0.5 minute
Above 30,000 feet	Inapplicable	2.5 minutes
Above 25,000 feet	Inapplicable	5 minutes
Above 20,000 feet	1 minute	Not Prescribed
Above 18,500 feet	Not Prescribed	10 minutes
Above 15,000 feet	2 minutes	20 minutes
Above 10,000 feet	10 minutes	No Time Limit

In interpreting the above proposal, the following points are made:

(1) The time durations above a given altitude include all the times at higher altitudes. For example, in Table II, Column B., the 5 minutes time allowed above a 25,000 foot cabin altitude, includes the 0.5 minute interval of exposure above 35,000 feet and the 2.5 interval above 30,000 feet;

(2) The data are based upon the assumption that there will be some type of cabin ascent profile with a variable dwell time followed by an unspecified type of cabin descent profile to the lower limit;

(3) In curves I B. and II B., it is assumed that all passengers will be breathing supplemental oxygen as soon after ascent above 12,000 feet is begun as feasible, and that to assure this, the cabin attendants will function during the emergency as "altitude chamber technicians" in that they will have donned portable oxygen equipment and will be active in tending to passengers who may not have donned their respective masks or may have improperly used them, thereby experiencing hypoxia and requiring aid;

(4) The 0.5 minute interval above 35,000 feet effectively shortens the maximum dwell time allowed in the December 29, 1967 tentative SST Airworthiness Standards in order that the possibility of nitrogen embolism may be diminished.

Comment on the Boeing Proposal

The Boeing proposal represents a parallel step in the development of standards for the SST, especially with respect to its recognition of finite ascent and descent times which are implicitly inversely related to one another under its provisions. For example, a slow cabin altitude ascent above a given level, say 25,000 feet in II B., must be followed by a rapid cabin altitude descent to achieve a return to the 25,000 foot level within the prescribed limit of five minutes. Conversely, a trade-off in the opposite direction is allowed, in that a rapid ascent under the same circumstances could be followed by a slower descent, still remaining in the five minute limits. A uniform rate of ascent from a 25,000 foot cabin altitude to 37,000 feet in 2.5 minutes would have to have an infinitely small dwell time at 37,000 feet in order to descend at the same rate to 25,000 feet within the five minute limit.

The Boeing cabin altitude profiles in I B and II B provide protection which is contingent upon all passengers utilizing oxygen within a reasonably short time, and to assure this, the cabin attendants must quickly and efficiently be independently mobile with self-carried portable oxygen units. The SST cabin attendants must be able to recognize the symptoms of incipient hypoxia in themselves and passengers, and circulate among the passengers, providing assistance with the masks where necessary. To expect cabin attendants to function in a fashion similar to "altitude chamber inside technicians" is to suggest the need for chamber training for such attendants.

A two and one half minute time above 30,000 feet in the absence of properly used supplemental oxygen, could likely yield irreversible central nervous system changes if the ascent were rapid, the dwell at 37,000 feet lasting thirty seconds, and descent to 30,000 feet occurring rapidly only at the end of the proposed two and one half minutes. If this were compounded by another two and one half minutes over 25,000 feet in the absence of properly used oxygen, the physiologic danger would be further compounded.

In utilizing as much of the Boeing proposal as possible in evolving the next developments under Part 25, allowances for those passengers who may fail to properly utilize this supplemental oxygen must be made from the environmental system airworthiness design standpoint, since cabin attendant duties and functions fall outside of the purview of Part 25 and within that of the Parts governing operations. Accordingly, the SST cabin profiles prescribed under Part 25, must return within a given time to the level from whence they started, that is, 8,000 feet, the minimally safe altitude for oxygenation of a representative passenger population, especially reoxygenation following an ascent with hypoxia.

Therefore, the proposal put forth later herein for type certification under Part 25 of the tentative SST Airworthiness Regulations will be somewhat more conservative than the Boeing suggestions. It is conceivable that as operational procedures are evolved, and airline cabin attendant training practices and other considerations (for example, the quality of passenger oxygen masks) are clarified and incorporated in the appropriate operating regulations, cabin altitude profiles along the lines of those suggested by

Boeing may, in fact, become operational. Studies are contemplated in which data on cabin attendant activity work-load capabilities under varying cabin altitudes including 37,000 feet are to be obtained. Studies are also contemplated regarding passenger oxygen mask considerations, including improved means of assuring proper mask donning and an adequate fit.

The basis of Boeing Tables I A. and II A., developed assuming no passenger supplemental oxygen is provided, reflects the present desire, articulated by some airline operators, to eliminate passenger supplemental oxygen equipment in the air carrier operating regulations. This topic will remain academic until the time of acquisition of hard data based upon appropriate flight experience with some prototype and production aircraft plus extensive ground pressure testing with the pressure vessels and systems of these aircraft, including an adequate number of pressure cycles. The saving of weight coupled with decreased maintenance costs are the usual primary considerations given to eliminating passenger oxygen.

Newer passenger oxygen systems utilizing "solid oxygen" ("chlorate candles") are coming available and are planned for the C5A and the new generation of "air busses" (L-1011, DC-10, etc.). These are lightweight, reliable, and present relatively low maintenance costs, thus offsetting to a considerable degree the "penalties" of providing passenger oxygen.

The FAR's provide no standards for the quality of oxygen delivered by solid oxygen sources, and, consequently, a regulatory project has been established to accomplish this. In connection with this project, some reliance will be placed upon the Navy submarine experience, wherein a heavy reliance is placed upon such sources for supplemental oxygen during prolonged underwater voyages. Presently, the FAA references the military specification (MIL-0-27210) as that recommended for "Aviators' Breathing Oxygen" to be used in civil aviation activities.

At this stage in the evaluation of the SST, in which hard data for exclusion of passenger oxygen from the SST does not exist, it is mandatory that planning for such oxygen proceed accordingly.

Although the SST will have passenger oxygen,[3] one aspect of hypothetical "oxygenless" passenger flight is the necessity of accomplishing "immediate" emergency descents when cabin pressure losses occur. Any delay on the part of crew members in initiating the descents is fraught with potential medical hazard to the passengers. If descents are made at rates producing pressure differentials across the eardrum in excess of 100 millimeters of mercury, drum rupture is very likely.[4] This is especially so if the individuals suffer from a common cold or other upper respiratory condition. Also, the lack of passenger oxygen precludes the opportunity for the crew to assess the mechanical status of the aircraft and decide the best time for descent and type of descent.

9. Passenger Pressurization Considerations

The following factors are delineated in preparing updated pressurization standards for SST passengers:

(1) The passengers will not be denitrogenated, a factor significant in bends development, especially above 25,000 feet;

(2) A given flight complement will very likely contain a significant number of individuals suffering from chronic cardiovascular and pulmonary impairments;

(3) A certain number of passengers may not get full utilization of their oxygen equipment during the period of the emergency (recent studies by Dr. Billings of Ohio State University indicate that a significant proportion of passengers may don existing masks erroneously—leaving the mouth or nose uncovered.)

It is felt that the BAC/SUD maximum cabin altitude limit of 35,000 feet is a proper goal, as is the Boeing proposal to limit the time to thirty seconds at 37,000 feet. For regulatory purposes, a 37,000 foot maximum with a more rapid descent profile, is considered to be equivalent to a lower cabin altitude or time with a slower descent.

It is also stressed that the proposed profiles are for SST FAR Part 25 certification, and that the aircraft may descend to any lower flight altitude necessary to assist the compressors in achieving the respective profiles.

A decompression is assumed to begin at an 8,000 foot cabin altitude and terminate when the cabin altitude returns to 8,000 feet.

Although the pressurization profiles developed for type certification of the SST provide for a specific altitude-time profile capability, it is recognized that under certain operational circumstances wherein new passenger oxygen protective equipment and briefing procedures are available, and the cabin attendants will be able to assist the passengers at elevated cabin altitudes, the profile times may be significantly extended as provided for in the appropriate operating regulations governing the flight.

10. Evolved and Updated Cabin Pressure Profile Capabilities for SST Passengers, Part 25

Limit I (No Passenger Oxygen)—This limit is for (a) a double failure in the pressurization system or (b) a single failure plus either (1) a 12-inch long skin puncture, or (2) complete loss of a door seal element, nine minutes at 15,000 feet with a return to 8,000 feet in the next minute. Time starts at the moment that cabin altitude exceeds 8,000 feet during the depressurization. Areas wherein the actual cabin altitude-time curve falls below the above criteria may be used to compensate, by integration, for areas wherein the actual cabin altitude time curve reasonably exceeds the above criteria. The time is concluded when the cabin altitude is back at 8,000 feet.

Limit II (Passenger Oxygen for All)—This limit is for the same failures as prescribed in Limit I. Seven minutes at 25,000 feet, with a return to 8,000 feet in the next three minutes. For example, if one assumes a hypothetical two minute initial ascent from 8,000 feet, the time at 25,000 feet will necessarily be contracted to five minutes. The same time determinants and integration procedures as in Limit I apply.

Limit III (Oxygen for 10% of Passengers)—This limit is related to an extremely remote emergency circumstance, such as one involving complete loss of a cabin window. One minute at 25,000 feet, with a return to 8,000 feet in the next five minutes. The same time determinants and integration procedures as in Limit I apply.

Limit IV (Passenger Oxygen for All)—This limit is related to an extremely remote emergency circumstance, such as one involving complete loss of a cabin window. One minute at 37,000 feet, with a uniform return to 8,000 feet over the next nine minutes. The same time determinants and integration procedures as in Limit I apply.

For altitude chamber validation purposes, the following profiles were selected and performed on December 13, 1968, at the Civil Aeromedical Institute:

			Chamber Altitude From (Feet)	Chamber Altitude To (Feet)	Duration (Minutes)	Tolerances
(No oxygen)	Limit I	ascent:	8,000	15,000	one	± 5 secs.
		dwell:	15,000	remain	eight	″
		descent:	15,000	8,000	one*	″
(With oxygen)	Limit II	ascent:	8,000	25,000	two	″
		dwell:	25,000	remain	five	″
		descent:	25,000	8,000	three*	″
(No oxygen)	Limit III	ascent:	8,000	25,000	two	″
		dwell:	25,000	remain	one	″
		descent:	25,000	8,000	three*	″
(With oxygen)	Limit IV	ascent:	8,000	37,000	three	″
		dwell:	37,000	remain	one	″
		descent:	37,000	8,000	six*	″

*Uniform return

In accomplishing the above four profiles, male subjects, between the ages of forty and fifty, and free of acute or chronic disease, were utilized. One subject was instrumented for ear-tip oximetry and sternal-lead electrocardiography, and participated in each profile.* All subjects were filmed during the tests and, in addition, a videotape record was made.

In these tests, Puritan airline passenger disposable oxygen masks (#114019), containing FAA TSO #C–64, were utilized for Limits II and IV. These masks are triangular in shape, contain an oxygen tidal inspiration reservoir and an "overboard" expiration valve. An airline passenger Puritan constant flow outlet valve assembly (#115010) was utilized. The oxygen flow rates were those utilized in civil aviation for jet passengers. The masks were donned in tests II and IV only after the chamber altitude exceeded 14,000 feet.

The following data were obtained during the four altitude chamber tests:

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* The author

Test One (Limit I)—Three subjects participated and no oxygen was utilized. As seen in the tabulation following the test four narrative, the blood oxygen saturation dropped to the 85% range. It was felt by the recording scientists that this reading was about five percent high due to photographic lighting entering the ear.

The heart rate was elevated slightly, approximating 100 beats per minute, with a peak of 105 in the seventh minute and climbing to 114 on recompression.

Some minor subjective symptoms of hypoxia were experienced (slight lightheadedness, etc.) and a few arithmetic computational errors were made.

Limit I

Time in Minutes	Altitude in Feet	Heart Rate in Beats Per Minute	Blood Oxygen Saturation In Percent
0.0	8,000	96	93
0.5	11,000	99	93
1.0	13,500	93	93
1.2	15,000	—	—
1.5	15,000	99	93
2.0	15,000	102	93
2.5	15,000	99	87
3.0	15,000	99	85
3.5	15,000	99	88
4.0	15,000	102	86
4.5	15,000	99	87
5.0	15,000	99	84
5.5	15,000	96	90
6.0	15,000	96	87
6.5	15,000	99	87
7.0	15,000	105	84
7.5	15,000	105	86
8.0	15,000	99	84
8.5	15,000	99	84
9.0	15,000	105	86
9.2	15,000	—	—
9.5	13,000	114	89
10.0	10,000	102	94
10.3	8,000	—	91

Test Two (Limit II)—Three subjects participated and oxygen was utilized.

The blood oxygen saturation remained above 90% during the entire profile. It is noted that the readings are about five percent high. The heart rate remained at about the 90 beats per minute level.

One subject got his oxygen mask elastic band wrapped around his spectacles, a circumstance which prevented mask donning. Had the decompression been to a higher altitude, loss of consciousness would certainly have occurred. At least thirty seconds was required to disentangle the spectacles, and this was accomplished only with help from the inside chamber technician. This subject experienced an ear-block on recompression and had to be disqualified from further flights.

Limit II

Time in Minutes	Altitude in Feet	Heart Rate in Beats Per Minute	Blood Oxygen Saturation In Percent
0.0	8,000	99	93
0.5	11,500	96	91
1.0	15,000	96	92
1.5	19,000	84	90
2.0	25,000	84	90
2.5	25,000	84	93
3.0	25,000	90	93
3.5	25,000	90	93
4.0	25,000	87	93
4.5	25,000	87	93
5.0	25,000	93	93
5.5	25,000	90	92
6.0	25,000	90	92
6.5	25,000	90	92
7.0	25,000	93	92
7.2	25,000	—	—
7.5	23,500	93	91
8.0	21,000	90	92
8.5	17,500	90	92
9.0	14,000	90	92
9.5	11,000	96	92
10.0	8,500	93	93
10.1	8,000	—	—

Test Three (Limit III)—Three subjects participated and no oxygen was utilized. Even though this profile was accomplished within six minutes, it brought the subjects to the brink of physiologic incapacitation.

The blood oxygen saturation fell to 66% during the third minute, a reading about five percent high as previously noted.

The heart rate climbed to 114 beats per minute from the 90–95 range, and returned to 99 at the sixth minute.

Subjective symptoms were extreme, including euphoria, giddiness, and an inability to accomplish simple arithmetic computations. Some cyanosis occurred in the third minute.

Limit III

Time in Minutes	Altitude in Feet	Heart Rate in Beats Per Minute	Blood Oxygen Saturation In Percent
0.0	8,000	96	92
0.5	12,000	90	90
1.0	17,500	90	86
1.5	21,500	102	82
2.0	25,000	105	75
2.5	25,000	111	66
3.0	25,000	114	66
3.5	22,000	108	71
4.0	19,000	102	79
4.5	17,000	102	85
5.0	14,000	108	94
5.5	10,000	99	93
6.0	8,000	99	100

Test Four (Limit IV)—Two subjects utilized oxygen after the 14,000 foot level was passed.

The ascent and descent rates caused little problem with respect to ear clearing with respect to the two subjects who were free of respiratory inflammation and who were familiar with the Valsalva maneuver for clearing the middle-ear.

The blood oxygen saturation remained above ninety percent. The heart rate remained after the second minute at the 90 beats per minute level (between the second and sixth minute the recording was lost due to air bubbles under the electrodes, but with extrapolation, probably approximated 90 beats per minute).

Subjective symptoms did not involve those resulting from hypoxia. The symptoms did include the sensation of abdominal fullness, especially at the end of the fourth minute (the gas volume expansion was approximately four times). Some flatus expulsion was experienced.

Limit IV

Time in Minutes	Altitude in Feet	Heart Rate in Beats Per Minute	Blood Oxygen Saturation In Percent
0.0	8,000	87	92
0.5	12,000	96	91
1.0	17,000	99	90
1.5	21,500	87	96
2.0	27,500	90	96
2.5	33,000	—*	96
3.0	37,000	—	90
3.5	37,000	—	91
4.0	37,000	—	92
4.5	34,500	—	95
5.0	31,500	—	93
5.5	29,000	—	93
6.0	27,000	90	94
6.5	24,000	93	96
7.0	21,500	90	95
7.5	19,000	93	95
8.0	17,000	93	96
8.5	14,000	87	95
9.0	12,000	87	95
9.5	9,500	93	95
10.0	8,000	87	95

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* See text

It was concluded that all four of the profiles fell within the limits of physiologic tolerances for the vast majority of the airline passenger population, recognizing that Limit III was the most marginal, and that Limit IV, for those who fail to utilize oxygen, could potentially yield irreversible nervous system changes. It is noted that the subjects utilized were clean-shaven and that the data do not necessarily apply to individuals with moustaches or beards (which may promote mask leakage of oxygen).

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Summary

The determination of regulatory altitude-time limits for the Supersonic Transport is a complex matter involving the interplay between (1) an oxygen requiring physiologic organism, (2) an "open" continuously pressurized engineering product, (3) an external operational environment exceeding pulmonary oxygenation capacities even with pressure-delivered oxygen, and (4) judgmental considerations regarding safety cut-off points.

All four of the above considerations must be included in the logic which leads to the establishment of a Federal Aviation Regulation governing pressurization malfunctions for Supersonic Transport type certification. Repressurization involves primarily (1) descent capability (2) compressor capacity, and, in the case of emergencies, (3) the nature of the failure (pressure vessel hole size, etc.).

An updated series of "critical cabin altitude" curves for passengers are presented, each qualified by the appropriate physiologic, environmental and equipment considerations which cannot be divorced from each determination of "minimally safe" circumstances from the regulatory standpoint. In developing these curves, personnel of the Federal Aviation Administration have "flown" through them in exact pressurization altitude-time simulations in the excellent altitude chamber facilities of the Civil Aeromedical Institute. The curves are based, therefore, upon studies reported in the scientific literature, results of actual inflight decompression experiences, and specifically undertaken "proving flights" in an altitude chamber.

The importance of establishing proper profiles must not be underestimated. Improper profiles might mislead design engineers into providing inadequate emergency recompression capabilities, and those persons providing the basis for such physiologic limits will surely be accountable when the SST is operational.

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