TIMES AVAILABLE FOR PROTECTIVE MEASURES IN EMERGENCIES AT HIGH ALTITUDE

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PROTECTION OF PASSENGERS AND AIR CREW FROM BLAST EFFECTS OF EXPLOSIVE DECOMPRESSION

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This brief review and summary of quantitative data from published (and unpublished) reports has been prepared as reference or background material for discussion of some considerations in high altitude operations, Air Transport Association Operations Conference, April 1951, Miami, Florida

April 1951

Part One

TIMES AVAILABLE FOR PROTECTIVE MEASURES IN EMERGENCIES AT HIGH ALTITUDES*

In explosive or extremely rapid decompression, some of the stresses may act upon man so rapidly as to preclude the possibility of applying remedial or protective measures, while others allow a brief or a relatively extended period for appropriate action.

(A) The rapid or "instantaneous" stresses include:

(1) Airblast. - Equalization of pressure differentials of about 3 psi. or more may result in airblast of sufficient force to lift a man and literally blast him from a cabin or cockpit. While the duration of the period of equalization may continue for one or more seconds, depending upon the internal volume of the airplane, the man is lost or has suffered severe impact force in tenths of a second. (See Part 2 for detailed effects of airblast.)

(2) Gas expansion. - "Instantaneous" expansion of the moist gases within the lungs and associated air passages and the digestive tract, occurs upon decompression. Distension of the intestinal gases may be both painful and dangerous but the degree of expansion resulting in these effects is well above that which can be expected even with very large openings in transport aircraft. The likelihood of the stress reaching maximum tolerable limits may be judged from the empirical formula for maximum relative gas expansion (tolerated by volunteer subjects) in a rapid or instantaneous decompression which is :

Relative gas expansion (REG) max. = 2.1 - 17.0t
where t is time in seconds. The maximum tolerated is taken as about 2.3. [1]

For example, a decompression would have to take place in 0.01 seconds for the REG to reach close to the value REGmax.

The chest acts very much like a rigid container. The air expelled from the lungs is approximately the volume which might be lost from a rigid vessel of the same capacity but may be somewhat greater. [2] The rate of flow may be very rapid, but in airplanes of the internal volume of passenger transport aircraft, this rate would probably not be greater than instantaneous rates of flow encountered in normal breathing during exercise (see Appendix "An explanation of some aspects of breathing").

1/ *H. M. Sweeney, Air Surgeon's Bulletin, October 1944*
2/ *F. G. Hall, AF Technical Report No. 6239, September 1950*

Thus, while expansion of gases contained within the lungs and gastro-intestinal tract is so rapid as to preclude protective measures, this stress probably does not constitute a serious problem in passenger air transportation. Theoretically, gases within the sinuses and in the middle ear may cause trouble but this is by no means certain. No reports of adverse effects on experimental subjects have been encountered. While it is granted that the subjects would be screened for chronic or temporary obstruction of the air passages, the fact that trouble occurs infrequently if at all may be significant.

(B) The delayed stresses:

While the period available for action may be very brief indeed, in light of the practical problem of providing protection to a large number of uninstructed passengers, there is sufficient time for suitable protective measures to be taken by each individual.

The delayed stresses include:

(1) Anoxia, Levels of tolerance. - Exposure to altitude, with consequent reduction of oxygen supply to the body, will produce a number of effects of various degrees of severity. Some of the signs which have been noted, and the oxygen blood levels at which they may occur are shown below. In the greatly simplified table below we assume that the time of exposure has been sufficiently long to produce the effects:

	Level or degree of effect	Approximate values for arterial blood oxygen (in per cent saturation)
1.	Deterioration (observer's judgment)	Probably 75% - 85%
2.	First error in card sorting. Time of useful consciousness. Just able to take sensible means for self-preservation.	Reported averages: one series 64%; another 67%.
3.	Imminent unconsciousness. Writing degenerated to meaningless scratches.	Reported averages for 4 series: 56%, 57%, 58%, 62%.
4.	Time to unconsciousness. Time to loss of consciousness. Loss of useful consciousness.	Reported averages, four reports: 51%, 54%, 60%, 65%.

Tolerances in terms of altitude and time. – Differences between the people who are exposed to reduced oxygen, differences in testing or estimating the level or condition, and differences in observers act to influence the results reported by various observers. (Charts 1* and 2 attached)

The charts emphasize the differences in individual tolerance reported by various investigators and demonstrates the impracticability of using average values (in Chart 2, for example, the average time of consciousness) in estimating time available for protection against stresses. If we assume a mean value, approximately one-half the passengers will have lost consciousness before remedial measures are provided. In consequence, protective measures should be designed on the basis of :

(a) the level of tolerance selected (for examples see Appendix I);

(b) the per cent of the group to be protected against stresses greater than at selected tolerance level.

The method of exposure also influences the time to attain the effect or criterion for the tolerance level being studied. For example, men who are exposed to high altitude as the result of mask removal, or other interruption of oxygen supply retain consciousness or useful consciousness longer than those exposed to the same maximum altitude after breathing air during a previous exposure to a pressure equivalent to a calm altitude of, say, 8,000 feet. (Charts 3 and 4)

There are far more data for tests that involve mask removal than for those involving decompression.

Absolute time for protection decreases with decreasing barometric pressure up to a minimum time beyond which there is no further reduction with increased stress. 3/ According to Luft, exposure of about 6-8 seconds at 50,000 to 55,000 feet will result in loss of consciousness at about 15-17 seconds after the beginning of the exposure, even if the subject has been recompressed to a tolerable pressure before he loses consciousness. The lag represents the time for the oxygen-poor blood to reach the brain, give up what oxygen it contains, and the brain cells to utilize the available store. Thus while anoxia can result in less than ten seconds, significantly longer times are available for instituting protective measures at 30,000 and 35,000 feet. (Charts 3 and 4)

(2) Aeroembolism. – This painful and sometimes incapacitating effect resulting from the evolution of gases dissolved in

* *The list of references to reports containing data used in the preparation of this chart may be obtained by written request.*

3/ *U. C. Luft, J. Aviation Med., in press.*

the fluids of the body occurs after an interval of minutes (usually many minutes) when ascent is made at the rates of a few hundred to a few thousand feet per minute. Further, Hitchcock et al [4] have studied 150 human subjects explosively decompressed. They found that, while bends may occur upon continued exposure, the average time at altitude without preoxygenation but with exercise at final altitude (35,000 feet) was 54 minutes. Age and certain physical conditions such as those with joint involvement may be expected to increase susceptibility to bends pain although there is little information on the minimal exposure times under those conditions. The theoretical possibility that aeroembolism might occur rapidly in explosive decompression should not be overlooked. On the basis of current information, it appears possible that descent will be made before this type of pressure stress will produce serious effect.

(3) Cold. - This is more likely to cause discomfort than to constitute a serious hazard provided that descent within a reasonable interval can be undertaken, and provided that the passengers were not exposed to a very high cooling rate resulting from both low temperature and high rate of air movement. Here again the order of magnitude of the period for effective protection is that of minutes even under very severe conditions.

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April 13, 1951
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Attachments: Part I
Charts 1 to 4, inc.
Appendix "An Explanation of Some Aspects of Breathing"

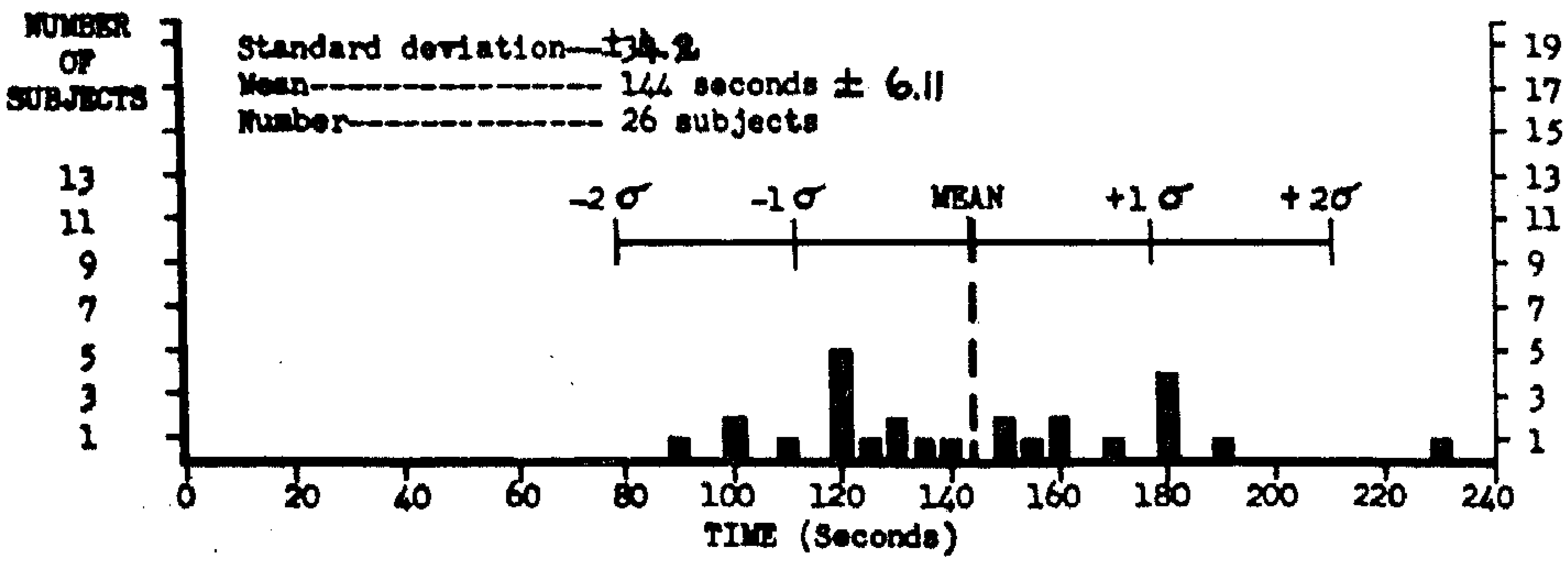
4/ *Hitchcock, Whitehorn and Edelman, J. Applied Physiology, Vol. I, December 1948*

TOLERANCE OF MAN BREATHING AIR
at an Atmospheric pressure
of 225mm (30,000 feet)

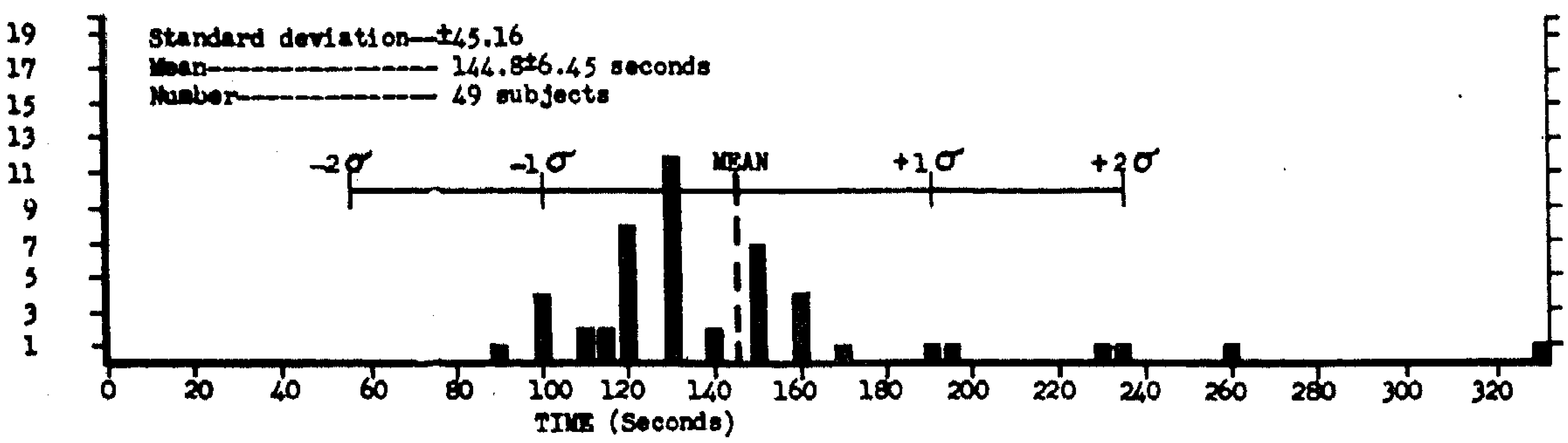
Distribution charts based on data from various sources.

Criteria of tolerance: Loss of Consciousness Imminent.

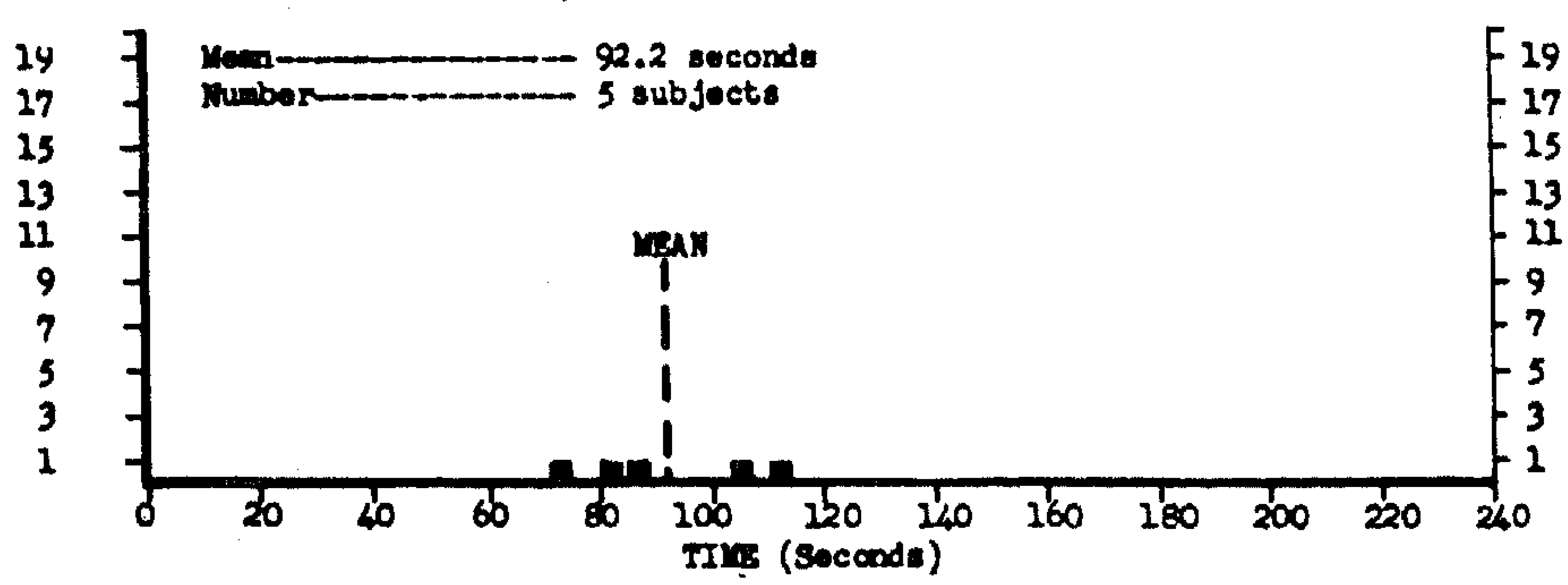
N.A.T.B., Pensacola, BuMed News Letter, Aviation Supplement, Vol. 5, August 31, 1945.



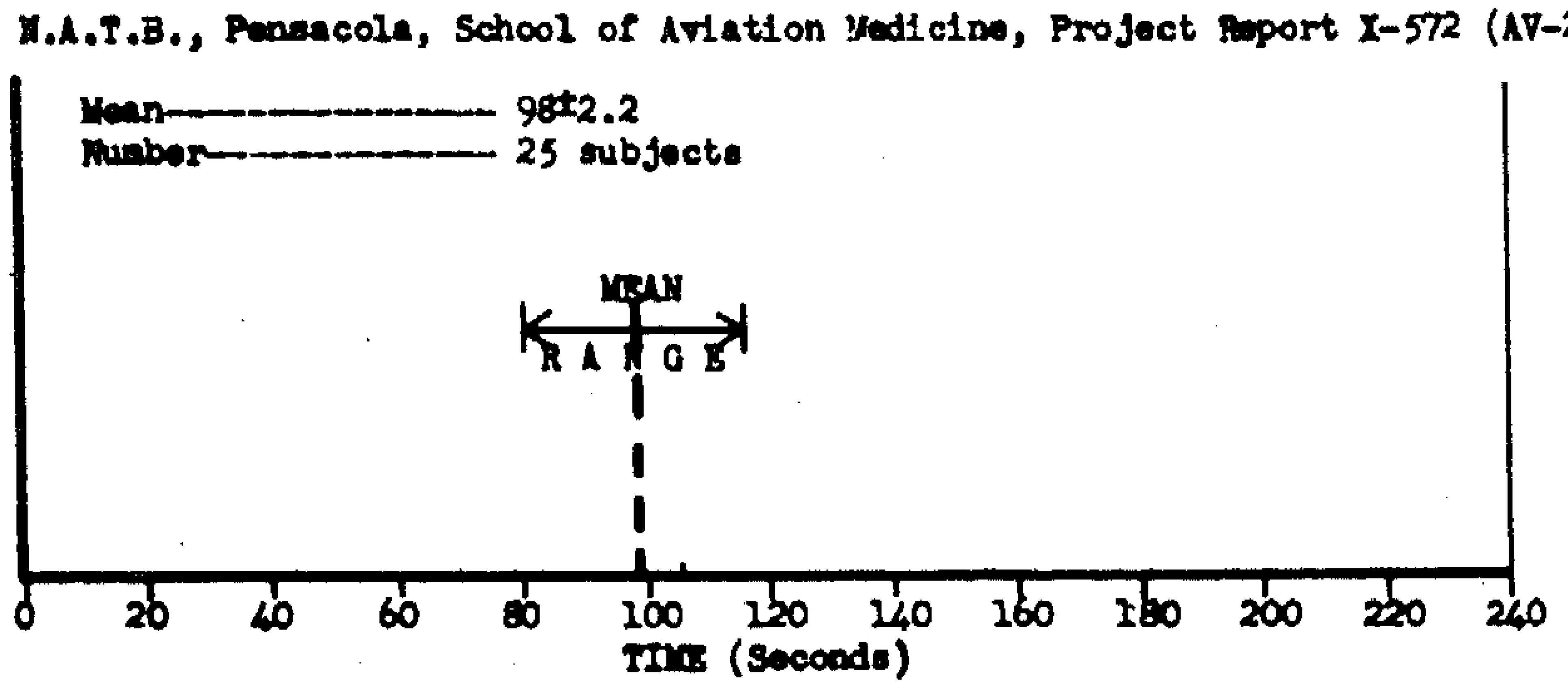
MacKenzie et al, Journal of Aviation Medicine, Volume 16, Number 3, June 1945.

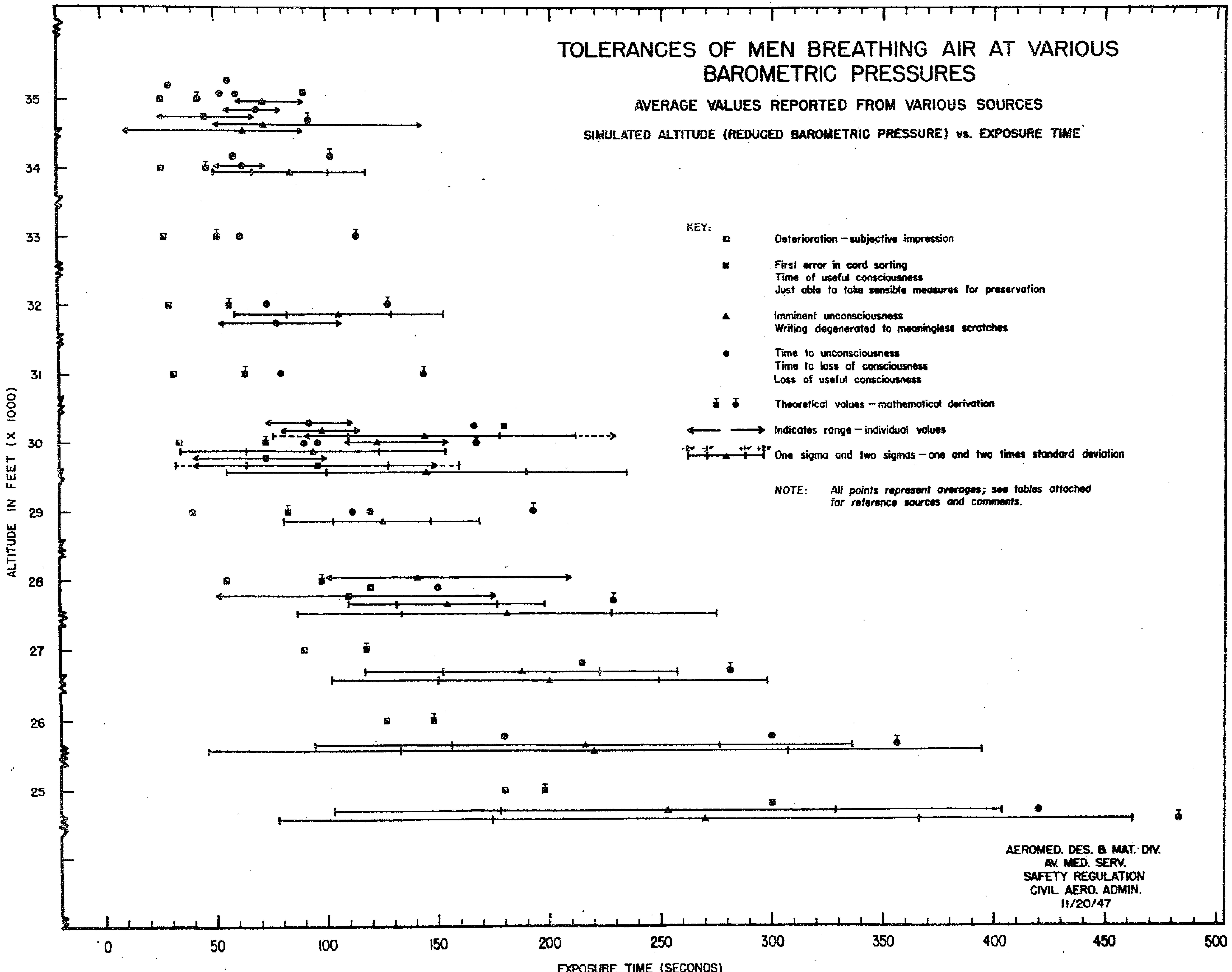


A.A.F. Materiel Center, Memo Report EXP-M-49-696-6A, November 27, 1942. (Appendix 2, Table 2)



N.A.T.B., Pensacola, School of Aviation Medicine, Project Report X-572 (AV-297-f), Report No. 1, Dec.1, 45

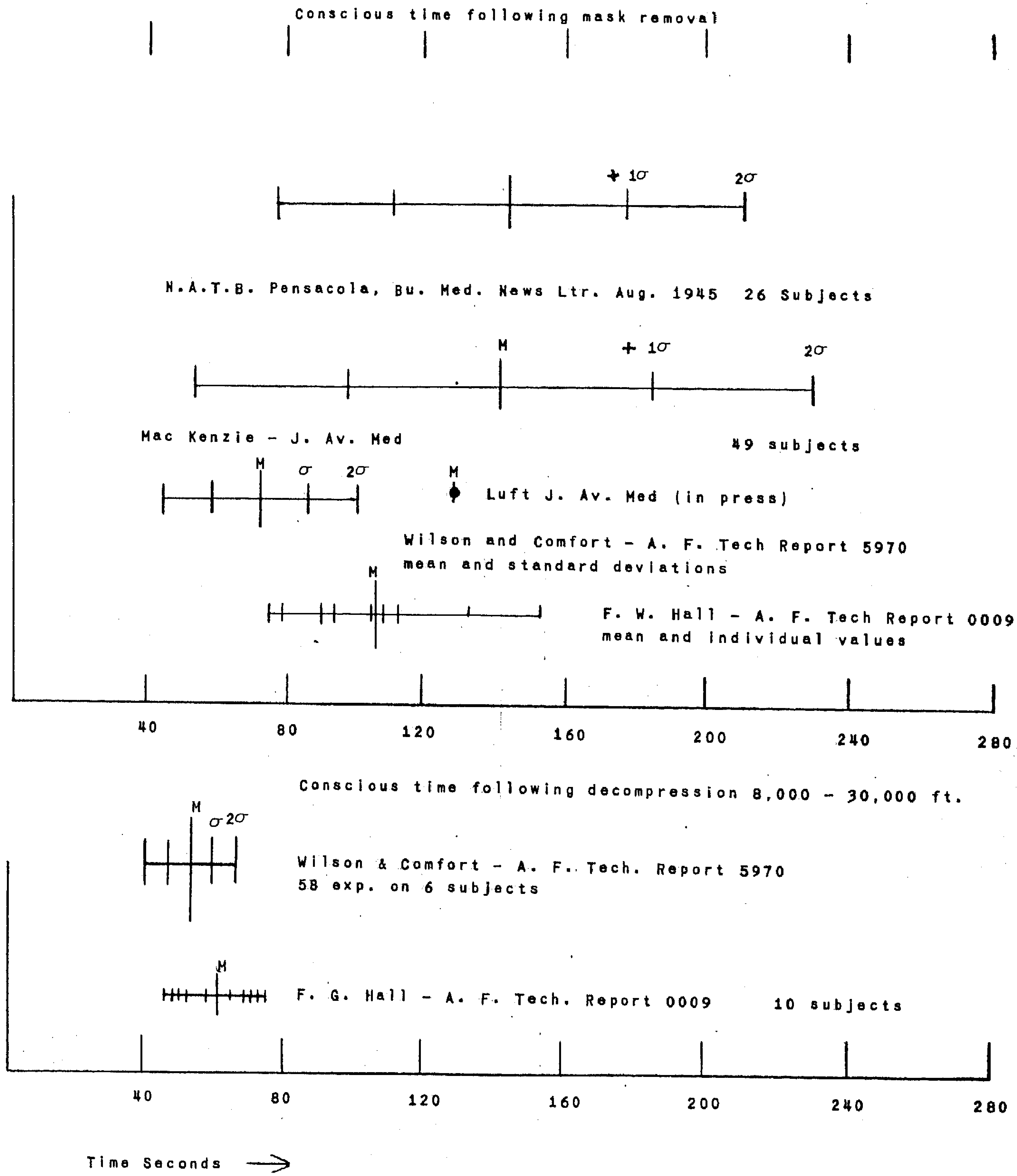




TOLERANCES OF MEN BREATHING AIR AT VARIOUS BAROMETRIC PRESSURES
AVERAGE VALUES REPORTED FROM VARIOUS SOURCES
SIMULATED ALTITUDE (REDUCED BAROMETRIC PRESSURE) vs. EXPOSURE TIME
KEY:
Deterioration – subjective impression
First error in card sorting
Time of useful consciousness
Just able to take sensible measures for preservation
Imminent unconsciousness
Writing degenerated to meaningless scratches
Time to unconsciousness
Time to loss of consciousness
Loss of useful consciousness
Theoretical values – mathematical derivation
Indicates range – individual values
One sigma and two sigmas – one and two times standard deviation
NOTE: All points represent averages; see tables attached for reference sources and comments.
ALTITUDE IN FEET (X 1000)
35
34
33
32
31
30
29
28
27
26
25
EXPOSURE TIME (SECONDS)
0
50
100
150
200
250
300
350
400
450
500
AEROMED. DES. & MAT. DIV.
AV. MED. SERV.
SAFETY REGULATION
CIVIL AERO. ADMIN.
11/20/47

Chart No. 3.

CONSCIOUS TIME AT 30, 000 Ft. (B. P. 226 MM HG)



B. G. King
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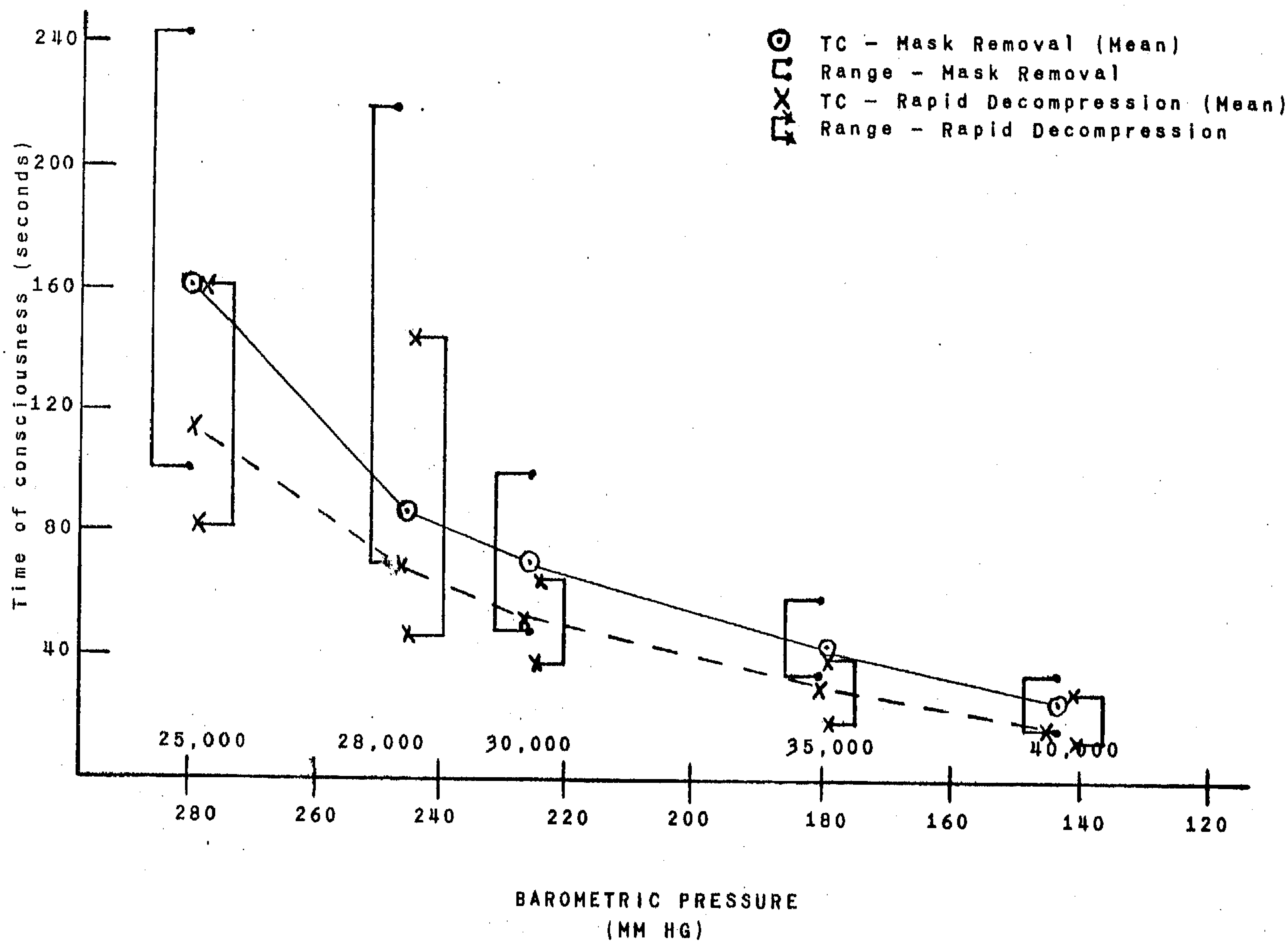
Chart No. 4



Traced from -
Wilson & Comfort
AF Tech Report 5970
Feb. 1950

Appendix one

AN EXPLANATION OF SOME ASPECTS OF BREATHING *

The amounts of oxygen required. – Man expends approximately 80 calories (317 + Btu) per hour when he is resting. When he works, his energy expenditure increases considerably. The energy, whether it takes the form of heat or of work, results from the burning, i.e., oxidation, of foodstuffs. About 1 liter of oxygen (760 mm Hg pressure and 0° C.) is required to produce 5 calories, so that even when a man is doing no work, he uses about 16 liters of oxygen per hour; this is about .267 liters per minute. There is roughly 21 per cent oxygen in the air he breathes into his lungs; only a portion of the oxygen is extracted from the air so that there is about 16.5 per cent oxygen in the air he breathes out. Thus oxygen "removal" or "recovery" is less than 22 per cent under resting conditions.

Let us assume that a man breathes 0.5 liter of air per breath. The half liter of air contains about 0.105 liter of oxygen; of this, man's net return per breath is 0.0225 liter of oxygen. On this basis he must breathe about 12 times per minute, with a turnover of 6 liters of air (containing 1.26 L/O_2) to get the oxygen he needs just to live. If he is at all active these values increase. Approximate values characteristic for various levels of activity are given below:

Work level	Power Ft. lbs. min.	Volume of air breathed (Minute Respiratory Volume) Liters per min.	Liters per min.
Resting	--	6-15	0.2-0.4
Light	2000	20-25	0.6-1.0
Moderate	3000	30-40	1.2-1.6
Hard	6000	40-60	1.8-2.4
Severe	8000	40-60	2.5-3.0

Flow rates in breathing. – Not only must a man be provided with a sufficient amount of oxygen, but that amount must be delivered at an adequate rate of flow. If the air or breathing mixture is not supplied at the required rate, a man must adjust his "breathing pattern"; if major adjustment is necessary he becomes conscious of the restriction to breathing and may develop "air-hunger" or feel that he is strangling.

It is important to remember that a man spends about one-half the time breathing in, and the other half breathing out. Therefore, if he breathes 10 liters a minute, the average flow rate at which air is drawn into his lungs is 20 L/min. The air flow during the time he is drawing a breath is not uniform, however, and peak velocities may be 3 to 4 times the flow rate per minute. Thus, even during moderate exercise man will require delivery of air or breathing mixture at a peak flow rate of 90 to 120 L/min.

**Prepared as reference or background material for discussion of some oxygen problems in high altitude operations; Air Transport Association Operations Conference, Miami, April 1951.*

Resistance to breathing. If there is interference with free flow of air so that a man cannot draw in air at the necessary peak flow rates without exerting perceptible suction, his breathing pattern will change, respiration will become difficult and he may suffer from air hunger. The absolute value of the negative pressure (as might be measured in an oxygen mask during inspiration) which is "perceptible" or annoying depends upon the peak velocity. Some illustrative values are:

Volume of air breathed (MRV) 1/min.	Peak flow rate of breath 1/min.	Resistance: Unnoticed (Peak negative pressure in mask in mm H_2O)	Noticed	Heavy
15	45-60	20	30	40-50
30	90-120	40	50	60

Transfer of oxygen from lungs to blood stream. It is, of course, the pressure, not the percentage, of oxygen that drives it through the thin wall between the air spaces in the lungs and the blood stream. Or, to be more accurate, it is the difference in the partial pressure of the oxygen in the lungs and that in the blood. At altitude, the percentage of oxygen in air remains the same, but the partial pressure of oxygen is reduced in proportion to the barometric pressure. If we take a liter of air to 18,000 feet, it would double in volume since the pressure is halved. Since we would have the same number of molecules of oxygen, they would be separated by twice the original distance from one another. In consequence, only one-half the former number of molecules would hit and pass through the lung membranes separating the air spaces and the blood vessels in unit time; the oxygen supply would be reduced.

There is, however, considerable adjustment for this in man--his heart beats more rapidly and the rate of circulation of the blood increases. Even more important, oxygen is carried principally in chemical combination with hemoglobin--and this combination occurs with remarkably little decrease in efficiency with decreasing oxygen partial pressures over a reasonable range. But now we are getting into too much detailed physiology. The point is that his oxygen supply is reduced (in spite of the compensation). That is why we add supplementary oxygen--to make the partial pressure of oxygen up to 149 mm. Hg, the same as it would be if man were breathing at sea level. Why 149 mm. Hg when 21 per cent of 760 is 159 mm. Hg? Well, as soon as man takes air into his nose and breathing passages, it is saturated with water vapor. Water vapor pressure at body temperature amounts to 47 mm. Hg; so, 760 - 47 = 149 mm. Hg.

Terms used in describing oxygen blood levels. - The amount of oxygen that the blood of the arteries can carry depends on the amount of hemoglobin present. If the blood is carrying an amount which represents its maximum capacity (i.e., the chemical combination between oxygen and hemoglobin has proceeded to completion under an oxygen pressure of about 150 mm. Hg or more), it is said to be 100 per cent saturated.

The adult male standard for oxygen-carrying capacity of the blood is generally taken as 0.0209 liter oxygen per 0.1 liter blood. Thus arterial blood is 100% saturated when each tenth liter contains 0.0209 liters oxygen. Most people become unconscious if their oxygen saturation falls to 50 to 60 per cent.

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April 13,1951

Part Two

PROTECTION OF PASSENGERS AND AIR CREW FROM AIR BLAST EFFECTS OF EXPLOSIVE DECOMPRESSION

Sudden loss of pressure as the result of structural failure in pressurized aircraft results in the immediate exposure of personnel to two major stresses: wind blast and lack of oxygen. The Civil Aviation Medical Research Laboratories have recently studied the effects of the air blast of explosive decompression on "passengers" seated at various distances from windows of the same dimensions as those found in some current transport aircraft. While the studies were undertaken for medical evaluation, two possible methods of protection of seated passengers and aircrew were observed. It is considered that the results of these trials may be of interest to aircraft manufacturers. The first method of protection considered is location of the seats beyond the boundaries of the danger area. The second is application of the simple principle of increasing the time of pressure equalization. Application of this latter principle appears to be practical, need not interfere with vision, and will not cause uneasiness since passengers will not be aware of its use.

This summary of results has been prepared for distribution limited to the branches of the aircraft industries and to military aviation groups. Prints of motion picture records of these trials have been made and are available to aircraft manufacturers, airline operators and cognizant units of the Armed Services on a loan basis upon request to the Civil Aeronautics Administration Regional Office.

Test procedures. - Explosive decompression trials were carried out with a range of pressure differentials of 2 to 7½ psi. between sea level atmosphere and the low pressure chamber. The internal volume of the chamber is 1350 cubic feet. The test windows were made up of plastic sheeting mounted in four types of metal frames; one had the same dimensions as a DC-6 and a Convair window (16" x 18", curved corners having a 3" radius), a Constellation 14" diameter circular window, and two non-standard windows, 10" and 8" in diameter. A dummy was used for all except the final check trials of "safe" positions. The dummy was constructed to simulate body dimensions, joint movements and joint resistance as closely as possible; the centers of gravity of the trunk and the limbs were closely approximated.

The pressure in the chamber was reduced to 6½ psi. below the existing barometric pressure. The dummy was placed in an airplane seat at various positions in relation to the window. The sheet plastic "window" was ruptured by a mechanical device carrying a metal plunger.

Results of these tests represent minimal safe distance since the volume of the chamber is less than that of pressurized aircraft. With the greater volume the increased duration of the air blast would be expected to increase the dimensions of the "danger area." On the other hand, the greater density of sea level air compared to density of cabin air pressurized to 8,000 feet ($\frac{P}{Po}$ = .78) affect the results in the opposite direction.

Results -- protection by distance. - Minimal safe distances between the window and the seat are shown on the accompanying chart which is based upon 100 trials at $6\frac{1}{2}$ psi. Moving pictures showed that the behavior of the dummy in any one position was consistent and reproducible. The dummy was lifted from the seat and blown through the window well into the chamber when the seat was in the conventional seat position.

The explosive decompression air blast had little or no effect on the dummy or on a human subject when the seat was moved inboard toward the aisle $7\frac{1}{2}$" or when it was moved straight back 15 inches behind its original position, the locations of the minimal boundaries at these and at other positions for various types of windows are shown on the chart. Within the "danger area" the dummy is either blown through the window or propelled against the inner structure with sufficient force to crush a human skull. Safety belts held the dummy in his seat but did not protect against crashing his head against the frame.

Dividing the DC-6 (or Convair) type window into four panels with panes 8" x 9" did not result in significant increase in safety since the dummy was still thrown against the frame and fuselage with dangerous if not lethal force when a single pane ruptured.

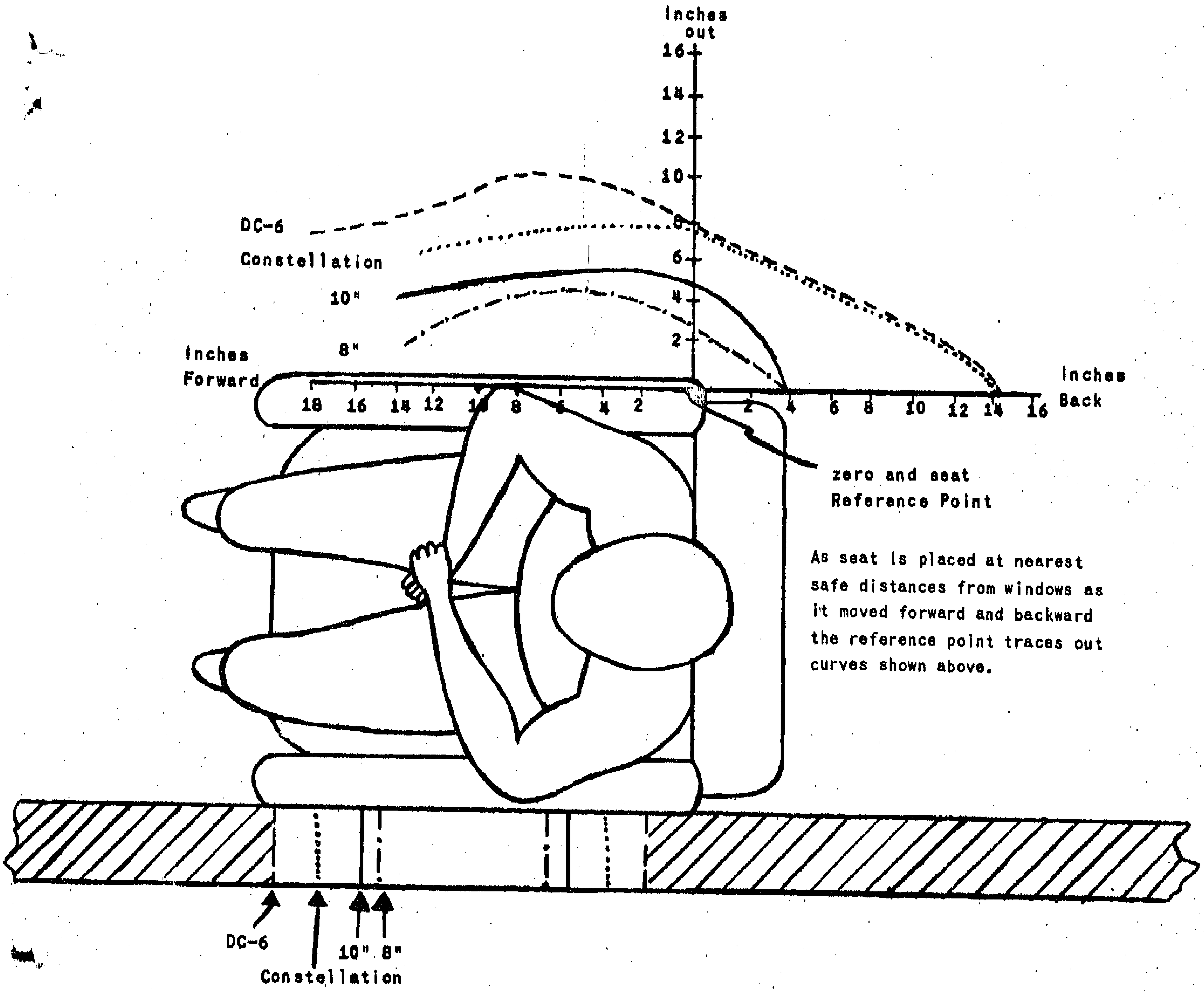
Results -- protection by increasing the time for decompression. - The principle of increasing the time for decompression by using multiple perforations in or around the inner window offers an effective and practical means of affording protection to persons seated with the seat arm directly against the window frame as in current conventional cabin arrangements. This is the same position from which the dummy is invariably blown through the window when no protection is provided; the safety afforded by the perforated window was demonstrated by trials with the dummy and with human subjects.

In the first trial in which the time of decompression was increased, a plastic spherical segment cut from a 25" B-29 blister to serve as the inner window over the DC-6 pressure window was drilled with 81 one-half inch holes, the total area of which was about 16 sq. inches. This area, equivalent to a window four inches square, increased the time of decompression from less than a second to 32 seconds and eliminated the hazardous wind blast effects of explosive decompression. A second series of tests was made on a perforated flat plastic window mounted inside the 14" circular Constellation window. The total area of the 27 apertures drilled in this window was over 5 sq. inches. The flat perforated inner window was satisfactory. As might be expected with the increased time for pressure equalization, a human subject experienced the explosive decompression without movement, ill effects or discomfort while sitting next to the window. Since perforations in the plastic itself would interfere with vision through the window and raise questions as to their purpose, a window was constructed mounting a solid sheet of plastic on a series of 1/2 inch blocks set two inches apart to allow the force of the blast to be dissipated around the periphery of the window. Here the total area of the apertures was 26 sq. inches and the decompression took place in approximately five seconds. This was also effective in protecting the dummy and a human subject. Engineering consideration of increasing the time for decompression by the use of multiple perforations at the edges of the plate or in the frame, or by the use of other means, can be expected to result in a design satisfactory for affording protection from air blast, and unobstructed vision without attracting notice or suggesting any possibility of untoward events to cause uneasiness of air-line passengers.

There are additional advantages of "controlling" or increasing the time for pressure equalization in explosive decompression emergencies, the loud report and fog which may cause panic or shock is eliminated. Further, the opportunity is afforded for covering the opening with damage-control mat or panel and providing passengers with oxygen before ill effects occur.

J. J. Swearingen
3 August 1950

MINIMAL SAFE DISTANCES FOR PROTECTION AGAINST THE WIND BLAST EFFECTS OF EXPLOSIVE DECOMPRESSION



MINIMAL SAFE DISTANCE CURVES

Civil Aviation Med. Res. Labs.
CAA Aeronautical Center
Oklahoma City
3 August 1950