DEVELOPMENT OF TECHNIQUES FOR EVALUATING THE PHYSIOLOGICAL PROTECTIVE EFFICIENCY OF CIVIL AVIATION OXYGEN EQUIPMENT

Ernest B. McFadden, M.S.

Approved by

J. Robert Dille, M.D.
Chief, Civil Aeromedical Institute

Released by

P. V. Siegel, M.D.
Federal Air Surgeon

April 1967

Office of Aviation Medicine

FEDERAL AVIATION ADMINISTRATION

Qualified requestors may obtain Aviation Medical Reports from Defense Documentation Center. The general public may purchase from Clearinghouse for Federal Scientific and Technical Information, U.S. Dept. of Commerce, Springfield, Va. 22151

DEVELOPMENT OF TECHNIQUES FOR EVALUATING THE PHYSIOLOGICAL PROTECTIVE EFFICIENCY OF CIVIL AVIATION OXYGEN EQUIPMENT

Ernest B. McFadden, M.S.

With the increased altitude capability of civil aircraft there has been a continuing and corresponding evolvement of new oxygen systems and masks.

The introduction of post World War II pressurized commercial transport aircraft flying at higher altitudes resulted in development of the KS passenger mask by United Air Lines. Designed to meet physiological requirements for supplementary oxygen and decompression to 25,000 feet, the mask was evaluated and introduced by Tuttle, Marbarger and Luft in 1951.[24]

The impending introduction of commercial jet transports flying at altitudes of up to 41,000 feet stimulated a hurried development of passenger oxygen systems and masks in the years between 1955 and 1959.[9, 13, 14, 21, 23] Blockley[4] describes some thirteen mask evaluations conducted at altitude during this period of time.

The possibility of decompression to the maximum flight altitude of this generation of aircraft dictated that passenger systems be capable of providing oxygen concentrations approaching 100%. This fostered the design of new types of continuous flow reservoir oxygen masks and automatically actuated presentation systems.

Studies of the physiological effects of rapid decompressions on passengers using this passenger mask design have been conducted by Donaldson[8] and Bryan.[6]

Disregarding inboard leakage, the continuous flow reservoir or phase dilution mask provides 100% oxygen at the most advantageous point in the respiratory cycle, that is, at the beginning of inspiration. If the oxygen flow is too low and the reservoir bag volume inadequate to accommodate the wearer's tidal volume, dilution, which occurs, does so toward the end of inspiration. Dilution so occurring may involve only the mask and anatomical dead space (Figure 1).

Assuming an adequate oxygen flow, the primary determinant of mask efficiency of this mask design becomes the existence and extent of inboard mask leakage and its effect on the inspired tracheal oxygen partial pressure. One basic disadvantage of all continuous flow oxygen systems is their inability to adjust automatically to the respiratory changes associated with variations in the emotional and physical activity of the wearer.

Concern with this problem is reflected in the Federal Aviation Regulations, Part 25 (formerly Part 4b), 25.1443,[10] which requires maintenance of a mean tracheal oxygen partial pressure of 83.8 mm Hg at a tidal volume of 1,100 cc and with a 30 liter (BTPS) minute volume for altitudes of 18,500 to 40,000 feet.

Standards for materials, testing and performance of this type of mask were set forth in a National Aerospace Standard (NAS 1179) in 1959.[2] This subsequently became a part of FAA Technical Standard Order C-64.[11]

Crew oxygen masks used in commercial jet transports have also undergone evolutionary change. Early versions of quick-donning masks were designed to be worn in the ready position on the person over the sternum. Crews complained that the masks, when worn in the ready position, compromised comfort and activity. Complaints have also been received that masks so worn soon become unsanitary depositories for food crums, spilled coffee, cigarette ashes and constitute a fire hazard.

In recent years the trend has been toward the quick-donning, hanging crew mask which is suspended in the cockpit within reach of the crewmember.

The possibility of rapid decompression dictates the importance of design as related to the ease and speed of donning, composition and volume of gases in the mask and breathing tube,[3, 4, 5, 7, 20]

and characteristics of the regulator. In addition, compatibility with eyeglasses and/or smoke goggles, peripheral visibility, comfort and communication must be considered.

Light, non-pressurized, supercharged aircraft are also being designed and manufactured with increased altitude capability. Manufacturers of this type of aircraft are re-assessing current available oxygen equipment searching for new equipment acceptable for use by relatively untrained private pilots and passengers. On January 11, 1966, at Upland, California, a stock model, single engine, Cessna Turbo-System Centurion set a new world altitude record for light aircraft of 39,334 feet. The flight was witnessed by representatives of NASA and recognized by the Federation Aeronautique Internationale, which certifies records in aviation.

This increased altitude capability of unpressurized light aircraft places a greater moral responsibility upon the oxygen equipment manufacturers, airframe manufacturers, aircraft dealers, medical organizations, and the Federal Aviation Administration, to provide the private pilot with simple, reliable and adequate oxygen equipment, plus a widespread and higher level of training and education in its utilization.

I. Methods.

A. *Passenger Masks.* Utilizing a variety of techniques, a number of evaluations of newly developed prototype passenger masks have been conducted. One of these was designed around minimum altitude increments and dwell time at altitude permissable under the National Aerospace Passenger Mask Standard (NAS 1179). The two specified alternative methods of determining mask performance (inspired tracheal oxygen partial pressure and oximetry) were simultaneously and continuously monitored and recorded. In addition, an attempt was made to maintain the 1,100 cc tidal and 30 liter/minute volumes specified in the Federal Aviation Regulations, using light exercise instead of voluntary hyperventilation.

The altitude chamber flight profile is shown in Figure 2.

After a preliminary test of the subject's capability to equalize ear pressures, the subject rested quietly at 10,000 feet until air-breathing ear oximeter readings indicated a stabilization of blood saturation. The chamber then ascended to 14,000 feet to establish a similar baseline at this altitude.

When it appeared the blood saturation had stabilized at 14,000 feet, the subject donned a crew type demand oxygen mask and commenced breathing 100% oxygen. Six subjects were instrumented as shown in Figure 3. A chamber safety observer accompanied each subject. Immediately following crew mask donning, exercise on a bicycle ergometer was initiated. The exercise level in RPM (Speed) and Watts (Load) was increased or decreased to stimulate and obtain the desired respiratory activity (approximately 25–30 liters/minute BTPS). This is regarded as a light to moderate workload approximately equivalent to walking at 3.0 to 3.5 miles per hour.

Exercise was continued until the desired minute volume as indicated by a calibrated dry gas meter was obtained and stabilized. A mass flowmeter (Technology, Inc. Model MFM–150–1) located in the mask hose also sensed and recorded the inspired tidal and minute volumes of the subject. The output of the mass flowmeter was fed into an integrator so that when a predetermined volume was sensed the unit would discharge and repeat. The subjects were denitrogenated during this period in an attempt to attenuate the increased bends potential due to exercise at the subsequent higher altitudes to be attained.

Continuing the exercise at the baseline level the subject held his breath, removed the crew mask, and rapidly donned the prototype passenger mask as shown in Figure 4. The flow of oxygen to the mask was regulated by an altitude sensitive regulator of the type used in multi-passenger oxygen systems of jet transport aircraft. The flow from this regulator instead of being transmitted directly to the subject was first routed outside the chamber through a flowmeter and needle valve arrangement in order to obtain precise measurement and control of flow.

The subject continued to exercise at the predetermined level as the altitude was increased to 40,000 feet. The chamber was leveled off and readings were taken at 14,000, 21,500, 29,000, 35,000 and 40,000 feet.

Two Custom Engineering and Development Company Model 300AR nitralizers were used to continuously measure end expiratory mask nitrogen. These instruments exhibit an initial re-

sponse time of 0.024 seconds, 90% response being obtained in 0.044 seconds. At the pressure setting used (0.6 mm Hg) the sampling rate was three cubic centimeters per minute. The continuous sample was drawn through a needle valve and microcatheter tubing (PE 60) of 0.030 inches internal diameter. The small, extremely light-weight microcatheter tubing connected to the mask did not require addition of significant weight or extensive modification of the mask, factors which might compromise the fit and operational characteristics of the mask. Mask leakage and tracheal oxygen partial pressures were derived from nitrogen analysis data obtained using previous methods of calculation [15,22,24].

A Waters Conley Ear Oximeter, Model XE-60A, was affixed to the antihelix of the subject's ear ten to fifteen minutes prior to the flight in order to allow warming and stabilization. The output of the earpiece was fed into an Electronics for Medicine oximeter amplifier and could be monitored on a panel meter and oscilloscope.

Ear oximeter results were recorded on a 14-channel Visicorder continuously throughout the chamber flight.

The signal from EKG electrodes was split and fed into an EKG monitor and cardiotachometer. Both of these signals were recorded on the Visicorder.

The output from the impedance pneumograph electrodes was fed into a Physiograph impedance pneumograph pre-amplifier and recorded on the Visicorder.

The impedance pneumograph was included in the experiment to attempt to determine if changes in the respiratory activity baseline occurred during subsequent ascent to altitude[12]. At the present time there is, to this author's knowledge, no satisfactory method of directly measuring respiratory minute and tidal volumes while wearing the passenger mask without compromising the performance of the mask.

B. *Crew Mask.* Evaluation of a prototype crew mask was carried out in three phases. The first phase consisted of exposing five crew members to a chamber flight profile as shown in Figure 5, with a maximum altitude of 43,000 feet while wearing the mask. The second phase consisted of rapidly decompressing five crew members from 8,000 to 40,000 feet in 45 to 50 seconds while wearing the mask and breathing 100% oxygen. The third phase consisted of rapidly decompressing these same subjects from 8,000 to 40,000 feet in 45 to 50 seconds and donning the mask during decompression. The donning signal was delayed for fifteen seconds after passing through 14,000 feet during the decompression.

Since subjects were well aware that they were to be decompressed, the basic fifteen-second delay was adopted after studying Bennett's[5] inflight determinations of the reaction and donning time of forty-two BOAC pilots subjected to surprise decompressions during training flights. It was anticipated that trained subjects would require approximately five seconds to accomplish donning following the donning signal. This would result in a total donning delay of approximately twenty seconds after passing through 14,000 feet. An analysis of Bennett's data by Blockley[4] indicates that 99% of the pilots would have completed donning within this time period. Instrumentation of subjects rapidly decompressed is shown in Figure 6.

Six subjects were used in these evaluations. Three of the subjects were transport pilots, one a flight engineer-student pilot, the fifth a chamber research technician-student pilot, and the sixth a physiologist.

In the first phase, a standard sentence was repeated on command during normal and pressure breathing, monitored and recorded for subjective evaluation of intelligibility. Crew member performance on a complex-coordinator was also evaluated during this phase under normal and pressure breathing conditions using commercial and military pressure breathing schedules.

Inboard leakage was determined during demand breathing by measuring the amount of nitrogen-containing ambient air (a convenient reference gas) entering the mask after the subject had completed respiratory nitrogen washout while breathing 100% oxygen. Outboard leakage was detected and estimated during pressure breathing by observing and measuring the slope of the mass flowmeter recording. During exhalation the recording tracing should remain horizontal, indicating zero flow.

The second phase utilized a profile which included a dwell time of 25 to 30 minutes at 8,000 feet to denitrogenate. The subjects, wearing the mask and breathing 100% oxygen, were then rapidly decompressed from 8,000 to 40,000 feet in 45 to 50 seconds.

The output of the Waters Ear Oximeter was fed into an Electronics for Medicine amplifier, displayed on a panel meter and oscilloscope and also fed into one of the two direct readout visicorders. The impedance pneumograph signal was amplified by a Physiograph and also recorded on one of the visicorders.

In the third phase four of the subjects were exposed to a profile similar to that of the second phase with the exception that the mask was removed after 25 to 28 minutes of denitrogenation at 8,000 feet and the subjects breathed air at 8,000 feet for two minutes prior to decompression. A fifth subject was rapidly decompressed from 8,000 to 40,000 feet without previous denitrogenation.

Prior to the decompression and during the time the subject was breathing air, the chamber safety observer would hang the mask back up in its retention device. During the decompression as the chamber passed through 14,000 feet an audible alarm bell alerted the subject. Fifteen seconds later and at approximately 25,000 feet a red donning signal light was activated and the subject donned the mask. Readout of the mass flowmeter and mask pressure transducer data indicated subject's completed mask donning at an altitude of 28,000 to 31,000 feet during decompression.

II. Results.

The intent of this paper is to describe several methods and techniques of evaluating unproven prototype passenger and crew masks at altitude in terms of applicable standards and regulations. Space does not allow presentation of detailed data obtained in each of a number of mask evaluations conducted. General results as applicable to critical analysis of two techniques are described.

Although the Federal Aviation Regulations specify a minute volume of 30 liters/minute and a tidal volume of 1,100 cc, this relationship was rarely obtained in our experiments. During previous evaluations carried out at ground level on ten female and ten male subjects[15], the tidal volume specified was attained by female subjects at an average minute volume of 18.5 liters/minute. At an average minute volume of 20.7 liters/minute male subjects exhibited a tidal volume of 1,430 cc.

During the altitude profile in Figure 2, the workload was increased during establishment of a baseline level in order to stimulate respiration to the 30 liters/minute level. An average minute volume of 27 liters/minute was attained with a concurrent tidal volume of 2,600 cc, over twice the 1,100 cc value specified in the Federal Aviation Regulations.

The concept of a 30 liters/minute volume and 1,100 cc tidal volume implies a respiratory rate of 27. The Federal Aviation Regulations were in part based on the assumption that an excited post-decompression passenger would exhibit a marked increase in respiratory rate with a moderate increase in tidal volume.

An empirical impedance pneumograph factor was calculated consisting of the ratio by which the mean amplitude varies from unity, which, for the purpose of these tests, was established as a baseline at 14,000 feet wearing the passenger mask.

The average impedance pneumograph factor decreased to 0.83 at 40,000 feet, indicating a slight reduction in tidal volume; however, the average respiratory rate increased from 16 to 18 off-setting the apparent decrease in tidal volume.

The impedance pneumograph amplitude is dependent upon changes in transthorasic impedance and has been shown to be directly related to the tidal volume[12].

As the oximeter indicated an average blood oxygen saturation of approximately 80% at 40,000 feet, it was expected hypoxic hyperventilation would occur. Continuous recording of the impedance pneumograph and respiratory rate failed to indicate a significant increase in ventilation during exercise at 40,000 feet over that of the corrected baseline obtained during exercise at 14,000 feet (average 89%) wearing the passenger mask.

Exercise time prior to ascending to altitude was held to a minimum in order to reduce the potential development of bends and reduce fatigue. Therefore, the initial air-breathing baselines at 10,000 and 14,000 feet were carried out under resting conditions.

According to NAS 1179, the air-breathing baselines are to be conducted with the subject engaged in the same level of activity as subsequently attained during evaluation of the mask at higher altitudes, but permits this to be carried out separately.

In order to investigate this factor, subjects breathing air were separately exposed to an alti-

tude of 14,000 feet while exercising at the predetermined baseline level. These tests indicated that exercise reduced the 14,000 feet air-breathing ear oximeter baseline readings by an average of 5%.

Following a flow curve slightly lower than used in jet transports[17], and increasing flow as required, oximeter readings of the subjects were maintained between an average of 85% at 21,500 to 80% at 40,000 feet during exercise, using an average oxygen flow of from 1.8 to 3.65 liters/minute NTPD.

Inboard mask leakage at 40,000 feet was low, with the nitrogen concentration averaging 3.4% and never exceeding 6%. The calculated mean tracheal oxygen partial pressures averaged 90 mm Hg.

B. *Crew Masks.* During the stepwise altitude profile in the first phase of the evaluation of a prototype crew mask, three subjects used an oxygen breathing regulator incorporating a reduced pressure breathing schedule. At 43,000 feet mask differential pressures using this regulator averaged 4.6 mm Hg upon inspiration and 11.5 mm Hg upon expiration.

Performance on the complex coordinator, requiring higher cerebral function dropped significantly. Although oximeter readings were not available in this phase, subjects exhibited subjective hypoxic symptoms to the extent that after three minutes at 43,000 feet, a descent was made and the remainder of the profile below 43,000 feet cancelled. The two remaining subjects, using an MD–1 regulator incorporating a military pressure breathing schedule, completed the chamber flight without incident.

In the second phase consisting of wearing the mask and breathing 100% oxygen during rapid decompression from 8,000 to 40,000 feet, oximetry indicated a slight (2–3%) drop in blood oxygen saturation. Tracheal oxygen partial pressures were also adequate. Immediately after decompression the impedance pneumograph amplitude increased by a factor of 3.5 times the baseline value.

The third phase consisted of donning the mask during rapid decompression from 8,000 to 40,000 feet in 49–51 seconds. Mask donning was accomplished in 29–34 seconds from the start of the decompression at altitudes of 28,000 to 31,000 feet. Data and time-motion analysis of motion pictures indicated donning was achieved in an average time of 4.80 seconds from the donning signal, with a range of 2.50 to 6.29 seconds. This data is in general agreement with Barron and Cook[3] who stated that their trained subjects required a minimum of three to four seconds to accomplish donning.

A sharp upward sweep in several of the mass flowmeter tracings shortly before initiation of the first breath after donning, indicated that the necessary altitude (28,000–31,000 feet) had been attained to activate the automatic pressure breathing characteristics of the MD–1 regulator. The system became free flowing until the mask was donned.

The oximeter demonstrated a marked transient drop in blood oxygen saturation 6 to 12 seconds after mask donning, being slightly more pronounced in the subject who had not denitrogenated (Figure 7). This delayed transient reduction in blood oxygen saturation was anticipated, having been demonstrated and investigated by Luft, Bryan, Donaldson, Barron and others[3,7,8,24].

A transient oximeter reading of 84% was the lowest recorded. After one minute at 40,000 feet the average saturation had returned to 96% with a mean mask pressure of 7.6 mm Hg.

The impedance pneumograph exhibited an average increase in amplitude of nine times the baseline value.

III. Discussion.

A. *Passenger Mask.* Previous high altitude evaluations of passenger masks have been carried out with the subjects in a resting or sedentary condition. In some of these evaluations a brief episode of voluntary hyperventilation was carried out in order to elevate minute volume to 30 liters/minute. This procedure is suggested in NAS 1179, but it is practically impossible for a sedentary subject to maintain this level of ventilation for more than two or three minutes without experiencing severe symptoms of hypocapnia (dizziness, paraesthesia, muscular cramps, etc.). In addition, the reduction of alveolar pCO_2 may unrealistically provide for an increase in alveolar pO_2. Changes in blood chemistry and cerebral blood flow due to hyperventilation also detract from its usefulness in mask evaluations[4].

A controlled and measured workload was used in this passenger mask evaluation in order to attempt to stimulate respiration to 30 liters/minute with an 1,100 cc tidal volume, without imposing

severe changes in respiratory and blood gas composition and chemistry.

One disadvantage of using exercise in mask evaluations at altitude is the increased susceptibility to the development of bends. The degree of denitrogenation, altitude profile and exposure time must be carefully considered in relation to the use of exercise.

In an altitude experiment, using jet transport flow rates and masks, true inboard leakage can normally be determined only at the 40,000 foot level or with an oxygen flow sufficient to prevent depletion of oxygen in the reservoir bag during peak inspiration. At altitudes below 40,000 feet the reduced flow into the mask may be deliberately diluted by introduction of air through the ambient air valve following depletion of oxygen in the reservoir bag. When determining true leakage the reservoir bag must be visually observed to confirm that it is not being emptied by the subject's tidal volume. If, however, there are significant and uncontrolled openings around the periphery of the mask, ambient air may be drawn into the mask during peak inspiration rather than through the non-return valve of the reservoir bag.

Continuous recording of mask nitrogen may indicate a sharp spike of up to 60–70% nitrogen. Continuous or transient dilution levels of alveolar oxygen are indicated if the spike is preliminary to establishment of a new and higher continuous level of dilution in the mask, or there is a significant nitrogen washout of the portion of ambient air introduced by a single leak during one inspiration.

Conversely, a simple spike without washout indicates the leakage has only penetrated the mask and anatomical dead space, having no effect on the alveolar pO_2.

At lower altitudes or increased tidal volumes, oxygen flow must be sufficient, so that the proportion of ambient air introduced does not lower the tracheal oxygen partial pressure below the specified level.

Determination of end expiratory nitrogen also provides a convenient estimation of dilution and calculation of tracheal oxygen partial pressure[22,24].

Considering the 1,100 cc volume of the reservoir one would deduct that a tidal volume in excess of 1,100 cc would result in introduction of ambient air during inspiration. However, at the maximum flow of 30 liters/minute BTPS at 40,000 feet, an additional 1000 cc BTPS may be introduced into the reservoir during the two seconds of inspiration.

In general, the ear oximeter, heart rate and impedance pneumograph readings were stabilized by exercise.

The wandering fluctuation of the ear oximeter was pronounced at 14,000 feet breathing air at rest, making establishment of baselines difficult, and generally was more variable than the calculated tracheal oxygen partial pressure.

Ground level evaluation of a passenger mask design[15] is also valuable in predicting the performance of a passenger mask at altitude. Determinations of mask leakage and tracheal partial pressures in one previous study at ground level[15] indicated that a mask design was inadequate. Subsequent rapid decompression of six subjects from 12,000 to 40,000 feet in 36–47 seconds wearing this mask design was carried out during resting and exercise[16]. Subjects wearing the mask and lightly exercising lost useful consciousness in 36–98 seconds as determined by inability to maintain sequential counting and the onset, frequency and duration of encephalographic slow waves. Three of the resting subjects demonstrated loss of useful consciousness in 67–250 seconds. One showed 6–7 cycle encephalographic slow waves only and two had no indication of loss of useful consciousness or encephalographic changes. One additional subject decompressed from 12,000 to 35,000 feet in 36 seconds exhibited intermittent bursts of 6–7 cycle slow waves, progressing to 3–4 cycle bursts, and returning to 6–7 cycle bursts, with no loss of useful consciousness detected.

This mask design exhibited leakage of sufficient magnitude that in only one instance, even when resting quietly, did the calculated tracheal pO_2 meet the minimum requirements of the Federal Aviation Regulations.

Standards for jet transport passenger mask performance are specified in terms of inspired tracheal oxygen partial pressures. In terms of physiological adequacy determination of alveolar pO_2 is a more desirable measure. Measurement of this parameter is generally not possible in the evaluation of passenger masks without compromising the performance characteristics of the mask. Polarographic oxygen sensors are being developed which hopefully may have sufficient

rapid response characteristics to allow end expiratory determination of the $p0_2$[18,19].

Early versions of polarographic sensors have been used in several of our evaluations of passenger oxygen masks with discouraging results, due to the very rapid and extreme changes of gas composition in the mask.

The Mass Spectrometer would be applicable to this situation were it not for the great expense involved.

In our experience the nitrogen analyzer with very rapid response and low sensing head pressures of 0.6 mm Hg (being at all times lower than the altitude chamber pressure) has been an easily calibrated and reliable instrument for measuring inboard mask leakage and indirectly estimating the inspired tracheal oxygen partial pressure.

B. *Crew Mask.* The prototype crew mask evaluated provided good protection at 43,000 feet when it was used with a regulator incorporating sufficient pressure to meet physiological requirements.

The suspension system and mask facepiece design limited inboard leakage during demand breathing and outboard leakage during pressure breathing to a minimal value. In one instance outboard leakage developed spontaneously during pressure breathing at 40,000 feet. Leakage was calculated at 10.4–10.9 liters/minute BTPS and ceased after two minutes. The pressure in the mask was unaffected by leakage of this magnitude.

Nitrogen washout following mask donning during decompression is shown in Figure 8. The initial washout at the beginning of denitrogenation at 8,000 feet is compared to the washout during rapid decompression from 8,000 to 40,000 feet in 49–51 seconds following two minutes of air breathing. The two-minute period of air breathing followed twenty-five minutes of 100% oxygen.

The third curve was derived from unpublished data obtained during evaluation of a similar type mask involving rapid decompression from 6,000 to 41,000 feet in 41–49 seconds. Subjects were breathing air at 6,000 feet with no previous denitrogenation prior to decompression.

These curves point out the delay imposed by equipment, anatomical and physiological dead space in reaching a high alveolar $p0_2$ after mask donning.

The breathing tube and mask at these decompression rates and donning altitudes would not be expected to contribute appreciably to the curve since the breathing tube had been flushed by oxygen two minutes previously; also the pressure breathing characteristics of the automatic regulator were observed to have been activated and the equipment flushed by free-flowing oxygen prior to donning.

The decompression rates of 40–50 seconds used in evaluation of the crew masks do not represent the maximum possible, but were decided upon after review of the calculated pressure loss rates for the B–707–131 (40 seconds) following loss of a cabin window, as presented to the FAA relative to mask approval.

IV. Conclusions.

The 1,100 cc tidal and 30 liters/minute volumes specified for passengers in the Federal Aviation Regulations were not duplicated by exercise. The 1,100 cc tidal volume was attained well in advance of the 30 liters/minute volume.

This does not imply that the regulation is inadequate, since all phase dilution masks, exhibiting an acceptable level of leakage and providing no less than 83.8 mm Hg inspired tracheal oxygen partial pressure, maintained subjects in a satisfactory physiological condition.

The characteristics of the phase dilution mask and the continuous high flows at the maximum altitude were sufficient to provide adequate passenger protection at tidal volumes imposed by exercise well in excess of those required by the Federal Aviation Regulations.

A mask design which allowed existence of significant and uncontrolled openings around the periphery of the mask was found to be unacceptable. Following redesign of the facepiece and valving, the mask provided adequate protection.

Compared to tracheal oxygen partial pressure, oximetry appeared to be a more variable but no less reliable index of the *physiological condition* of the mask wearer. Tracheal oxygen partial pressure appears to be a more reliable and practical index of *passenger mask performance.*

During rapid decompression from 8,000 to 40,000 feet in 49 to 51 seconds, crew mask donning was accomplished in 29 to 34 seconds from the start of decompression at an altitude of from 28,000 to 31,000 feet. Donning was accomplished in 2.5 to 6.3 seconds following the donning signal.

There was significant delayed transient decrease in blood oxygen saturation as indicated by the oximeter without loss of consciousness followed by rapid recovery.

The rapid decompression and mask donning experiments, in addition to providing information relative to unproven crew equipment, also point out practical limits of protection provided within the parameters of the decompression altitude and times evaluated.

Jet transport passenger and crew masks are used operationally only in an emergengy and for brief durations. This does not allow operational experience at altitude to be gained with these masks prior to a pressure loss emergency. This emphasizes the importance of human evaluation and testing of new, unproven, continuous flow, oxygen mask designs at altitude prior to approval and certification.

REFERENCES

1. ARO EQUIPMENT OF CALIF.: Qualification Test Report, Passenger Oxygen Mask. QTR 59–6. Los Angeles, Calif., June 24, 1959.
2. AEROSPACE INDUSTRIES ASSN. OF AMER.: National Aerospace Standard, NAS–1179.
3. BARRON, C. I., COOK, T. J.: Effects of Variable Decompressions to 45,000 Feet. *Aerospace Med.* 36:425, 1961.
4. BLOCKLEY, W. V., HANIFAN, D. T.: An Analysis of the Oxygen Protection Problem at Flight Altitudes Between 40,000 and 50,000 Feet. Final report on Contract FA–955, Federal Aviation Agency, Feb. 20, 1961.
5. BENNETT, G.: Reactions and Performance of Pilots Following Decompression. *Aerospace Med.* 32:134, 1961.
6. BRYAN, C. A. and LEACH, W. G.: Physiologic Effects of Cabin Pressure Failure in High Altitude Passenger Aircraft. *Aerospace Med.* 31:267, 1960.
7. BRYAN, C. A.: Aircrew Oxygen Requirements in High Altitude Transport Aircraft. Report No. IAM 59/4, RCAF Institute of Aviation Medicine, Toronto, Canada, Sept. 15, 1959.
8. DONALDSON, R. T., CARTER, E. T., BILLINGS, C. E., and HITCHCOCK, F. A.: Acute Hypoxia During Rapid Decompression and Emergency Descent in a Commercial Jet Aircraft. *Aerospace Med.* 31:842, 1960.
9. DRAYTON, F. A. and CARLSON, L. D.: Evaluation of Prototype Passenger Oxygen Mask Assemblies, Report No. D6–1954. Boeing Airplane Company, Transport Division, Feb. 9, 1959.
10. FEDERAL AVIATION REGULATIONS, Part 25, Airworthiness Standards, Transport Category Airplanes.
11. FEDERAL AVIATION AGENCY, Technical Standard Order C–64, Aug. 23, 1961.
12. GEDDES, L. A., HOFF, H. E., HICKMAN, E. M., and MOORE, A. G.: The Impedance Pneumograph, *Aerospace Med.* 33:28, 1962.
13. KOESTER, N. B., and EHRMANN: Emergency Oxygen Mask Development and Tests. Scott Engineering Report No. 554, Nov. 30, 1956.
14. MCFADDEN, E. B.: Time Factors in Passenger Utilization of Emergency Oxygen. Office of Aviation Safety, Civil Aeronautics Administration, Preliminary Report, May 1955.
15. MCFADDEN, E. B., RAEKE, J. W., and YOUNG, J. W.: An Improved Method for Determining the Efficiency of Crew and Passenger Oxygen Masks. Report 62–21. Federal Aviation Agency, Civil Aeromedical Research Institute, Oklahoma City, Oklahoma, Nov. 1962.
16. MCFADDEN, E. B., TANG, P. C., and RAEKE, J. W.: Continuous Functional Testing of Passenger Masks at Ground Level and During Rapid Decompression. Presented at the Space and Flight Equipment Association, National Flight Safety, Survival and Personal Equipment Symposium, Oct. 28, 1964 (Unpublished).
17. MADDOCK, R. W.: A Design Analysis of a Jet Transport Passenger Oxygen System, Report No. SM–42564, Missile and Space System Division. Douglas Aircraft Company, Santa Monica, Calif., Mar. 1963.
18. NEVILLE, J. R.: Continuous Functional Testing of Oxygen Breathing Equipment. *Aerospace Med.* 34:1020, 1963.
19. NEWBERRY, P. D., AZIZ, J. P., and STUBBS, C. D.: A Method for Continuous Monitoring of the End-Tidal Partial Pressure of Oxygen. *Med. Serv. J. Canada* 20:745, Oct. 1964.
20. PRESTON, F. S.: Results of Decompression Trials in Chamber Appraisal of 3 Types of Aircraft Oxygen Mask Suspensions. British Eurpean Airways, Apr. 1959.
21. REUTERSKIOLD, C.: Project Bag, A Passenger Oxygen Mask For High Altitude Aircraft. Scandinavian Airlines System. Stockholm, Nov. 1956.
22. SOLLAMI, B. J.: Final Report on the Investigation of Mask Leakage in Passenger Oxygen Masks. Pioneer-Central Division, The Bendix Corporation. Federal Aviation Agency Contract FA–885. Feb. 1962.
23. SWEARINGEN, J. J.: An Adhesive Type Oxygen Mask. *J. Aviation Med.* 28:19–22, 1957.
24. TUTTLE, A. D., MARBARGER, J. P., and LUFT, U. C.: KS Disposable Oxygen Mask. *J. Aviation Med.* 22: 265, 1951.
25. USAF SCHOOL OF AVIATION MEDICINE: Respiratory Physiology in Aviation. Sept. 1954.

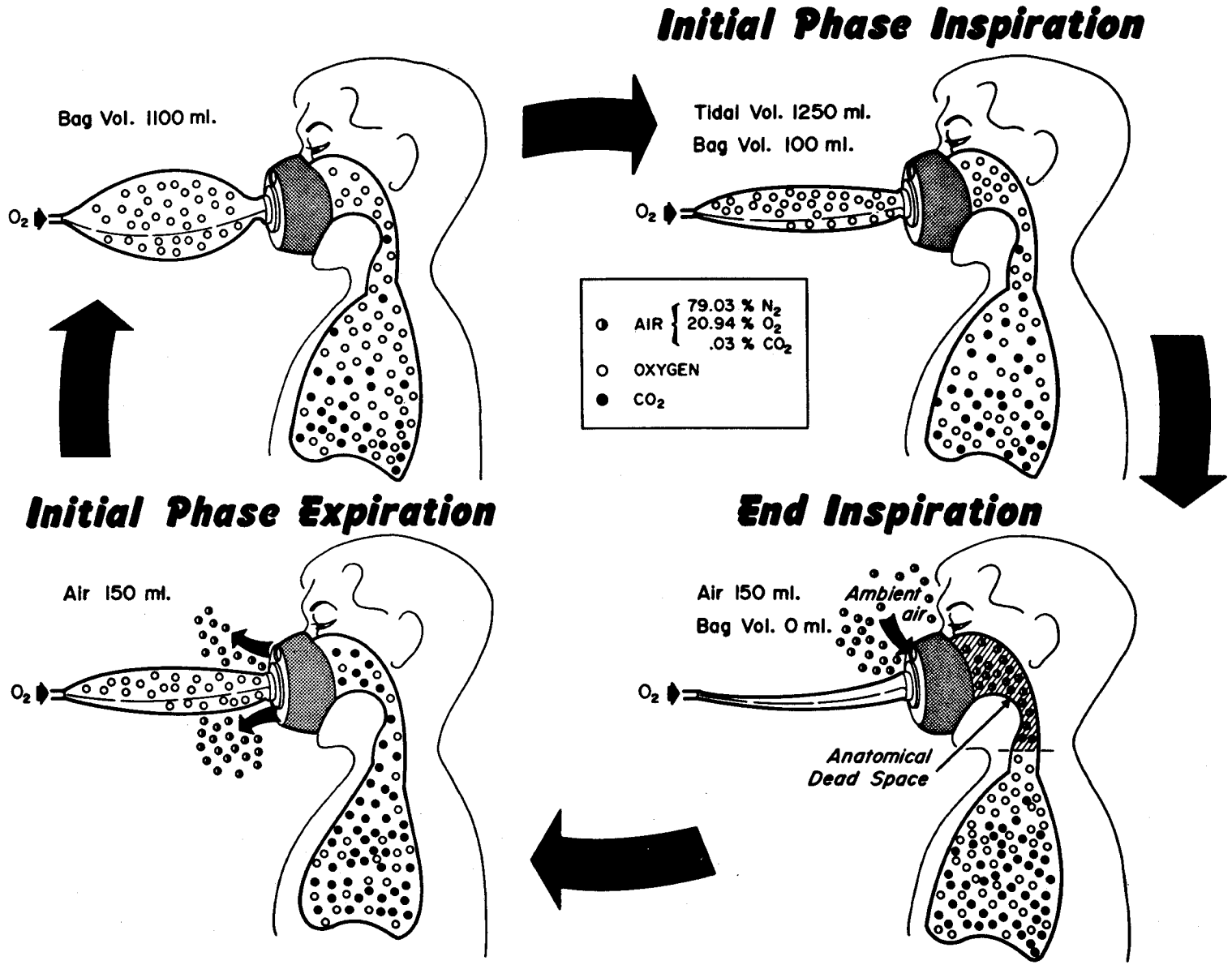

FIGURE 1. Functional characteristics of the NAS 1179 reservoir or phase dilution constant flow passenger oxygen mask. For clarity the diagram indicates flow stops at end of expiration. Actually some 1,000 cc of oxygen may be introduced into the reservoir bag at maximum jet transport flow rates during a 2 second inspiration.

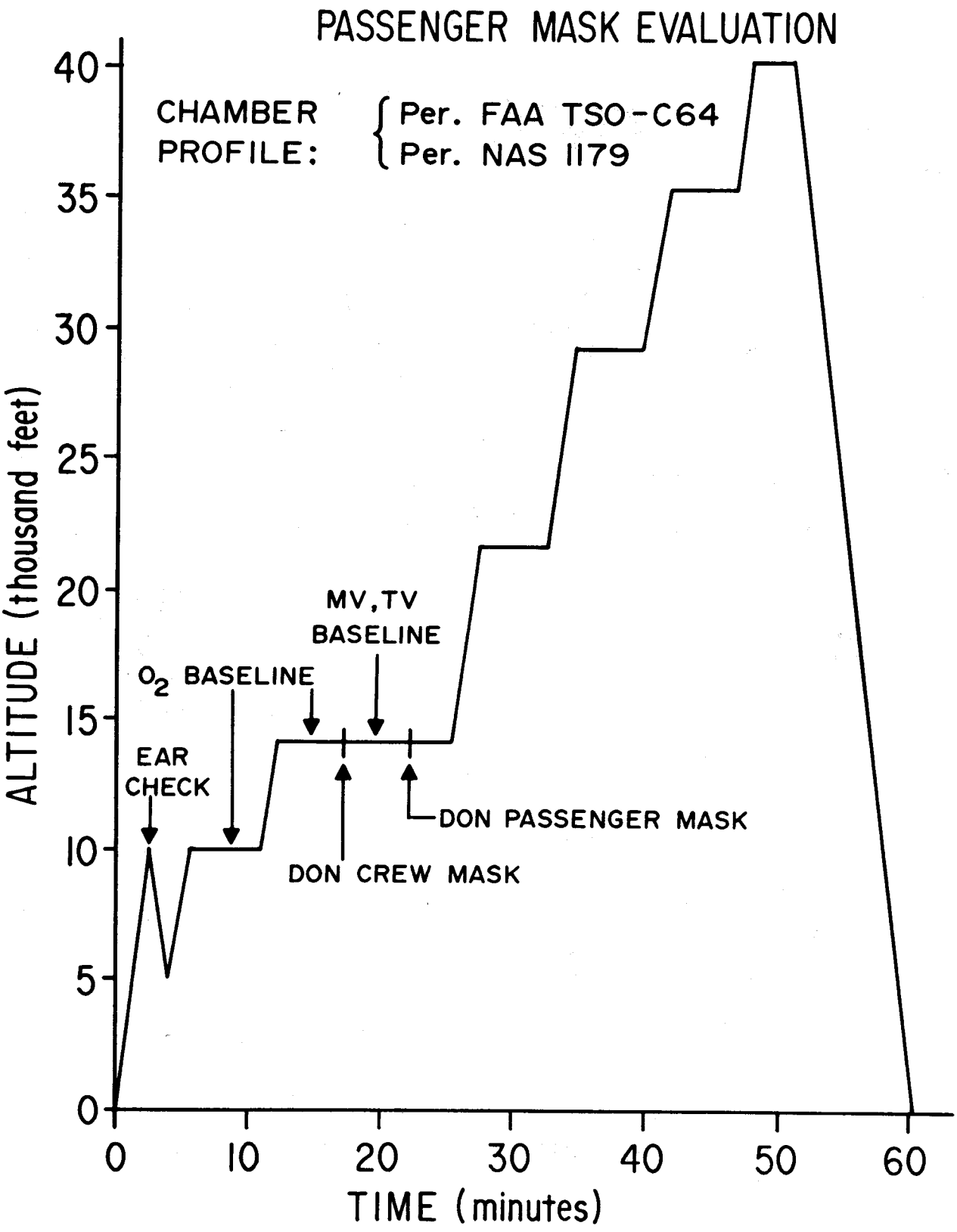

FIGURE 2. Basic altitude profile as designed to minimum altitude increments and duration of NAS 1179. Oximeter, minute and tidal volume baselines were continued until stabilized and were of variable duration.

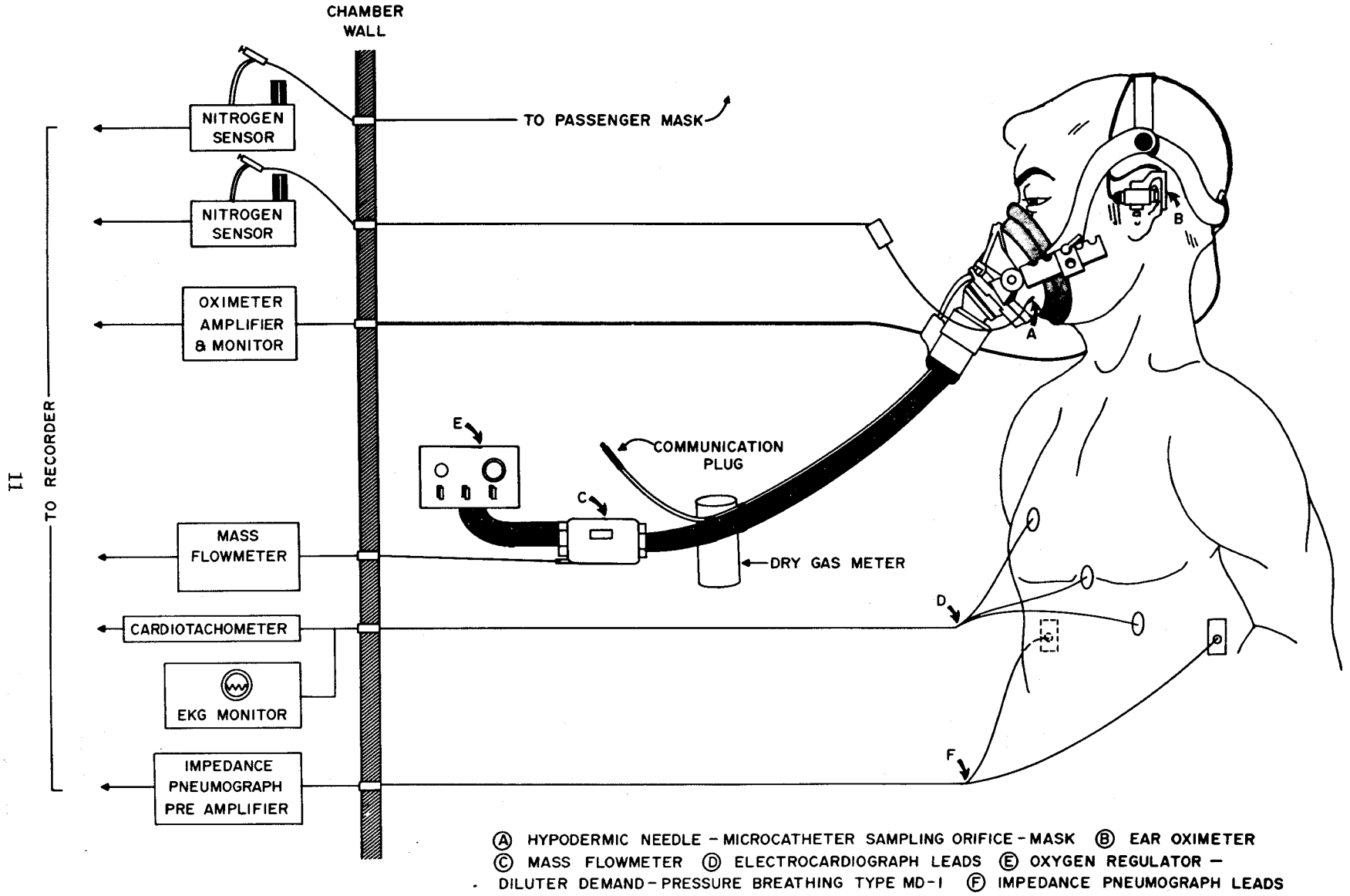

FIGURE 3. Instrument of subjects during nitrogen washout and establishment of minute and tidal volume baselines by exercise.

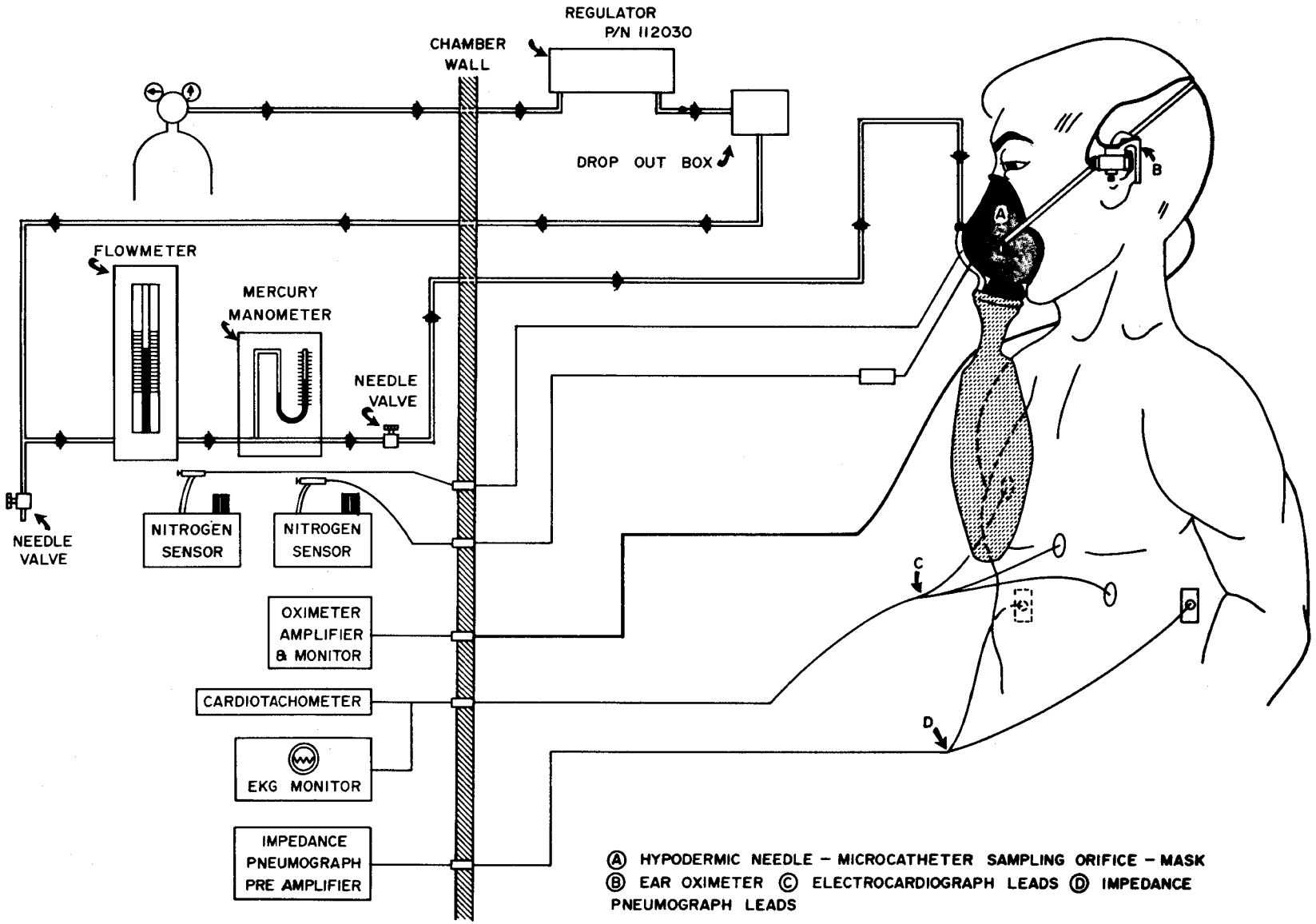

FIGURE 4. Instrumentation of subjects during passenger mask evaluation.

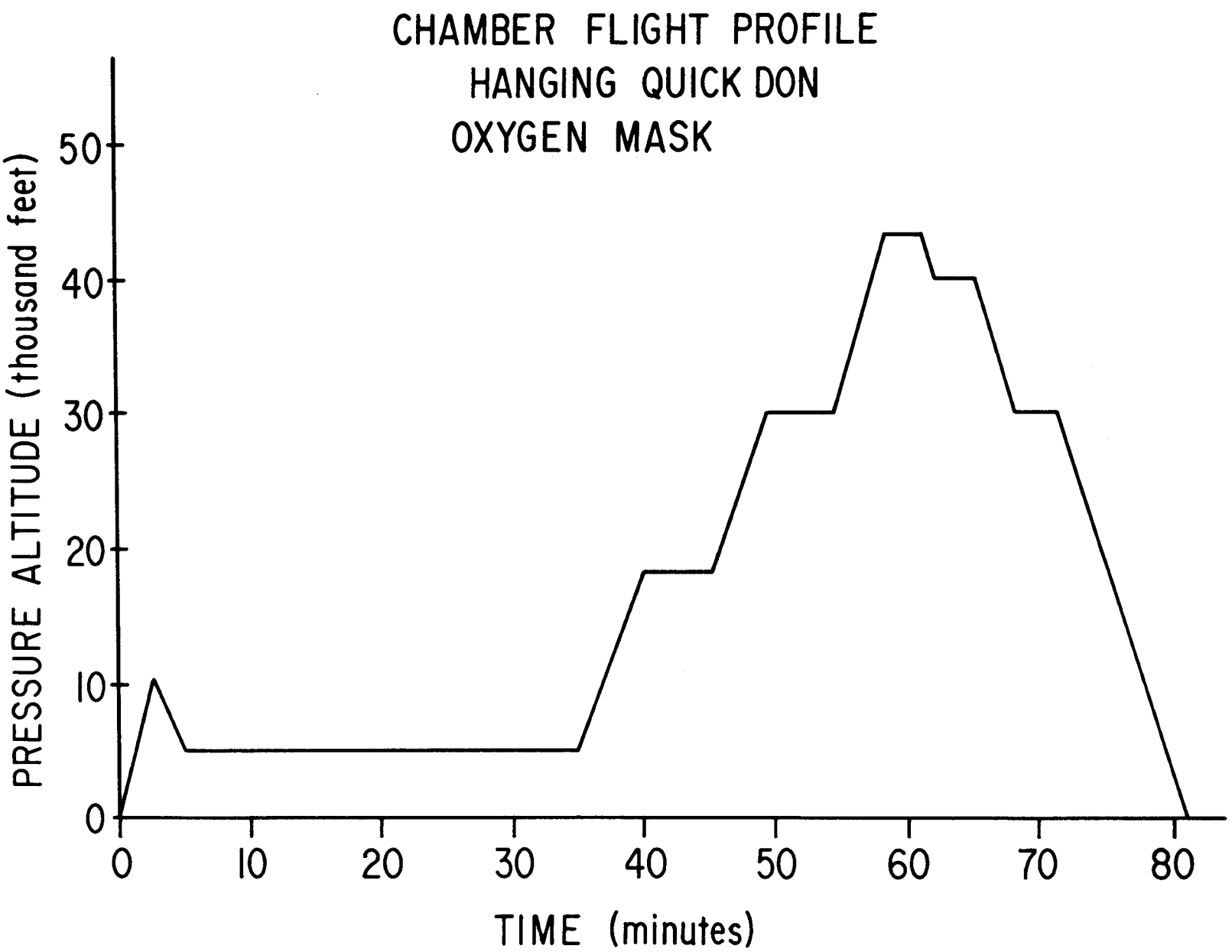

FIGURE 5. Altitude chamber flight profile used in the first phase of a hanging quick-don crew oxygen mask evaluation.

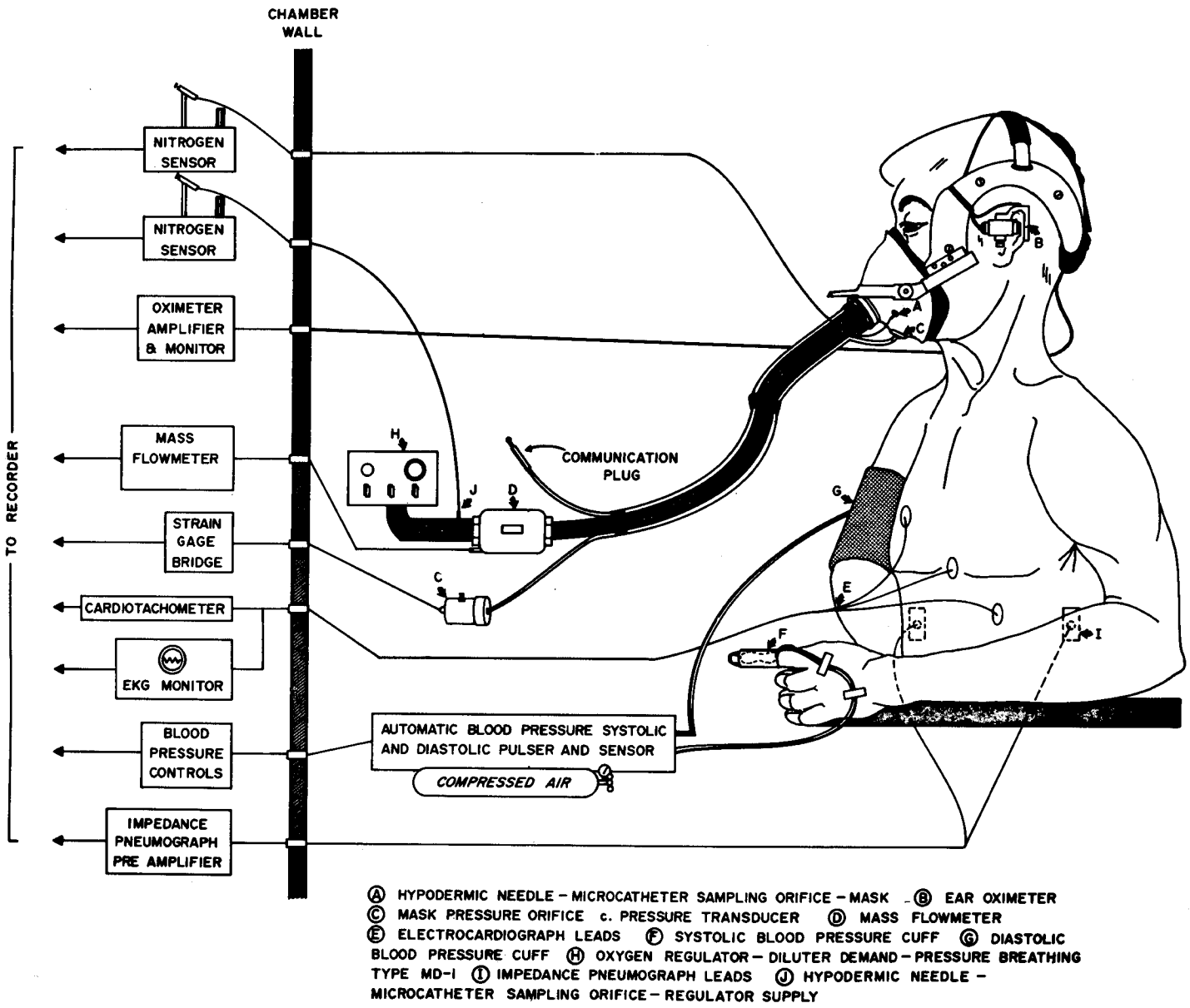

FIGURE 6. Instrumentation of subjects exposed to rapid decompression from 8,000 to 40,000 feet.

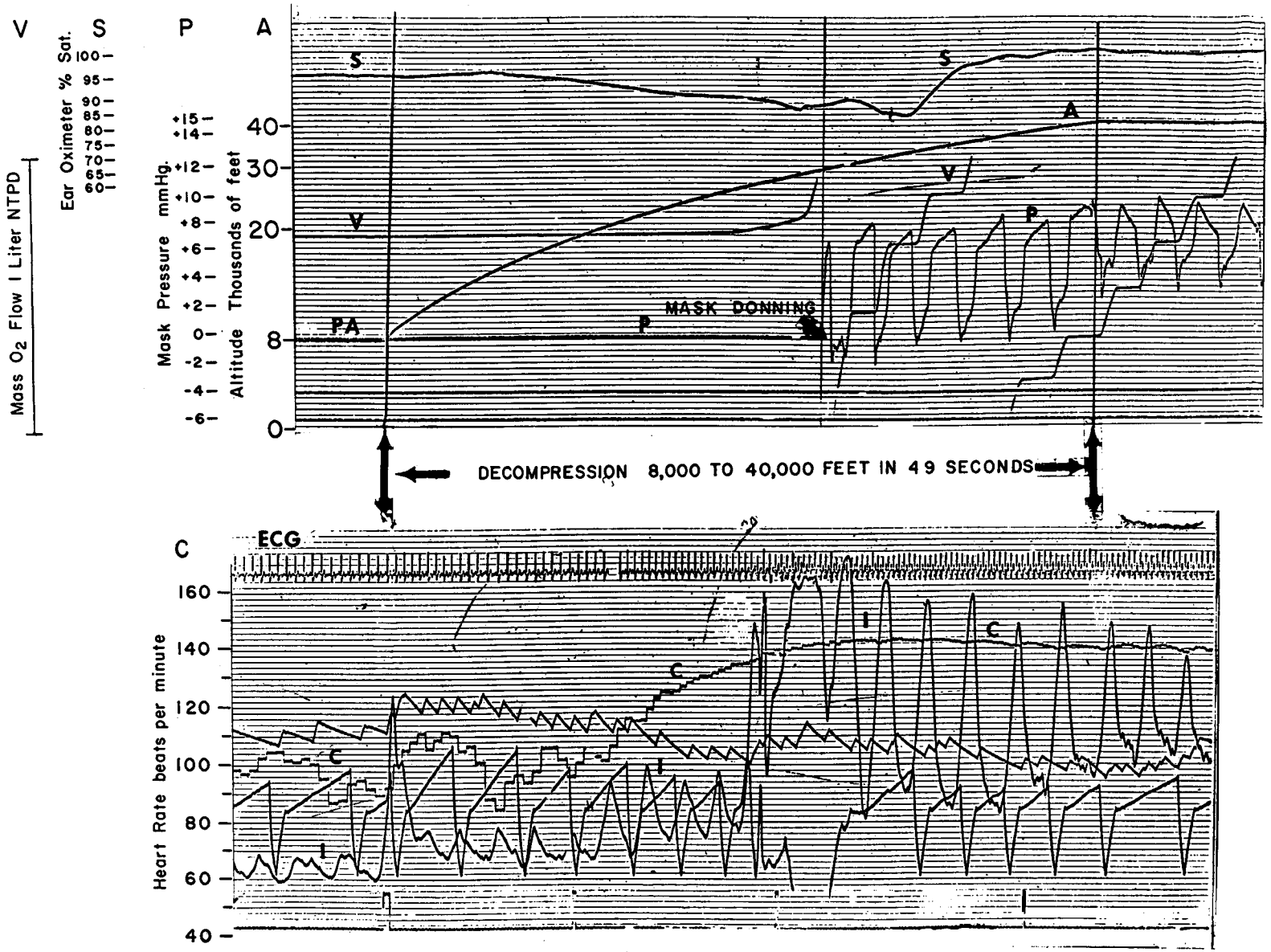

FIGURE 7. Mask donning during rapid decompression.

P—Mask Pressure
A—Altitude
C—Heart Rate
S—Oximeter
I—Impedance Pneumograph
V—Mass Flowmeter

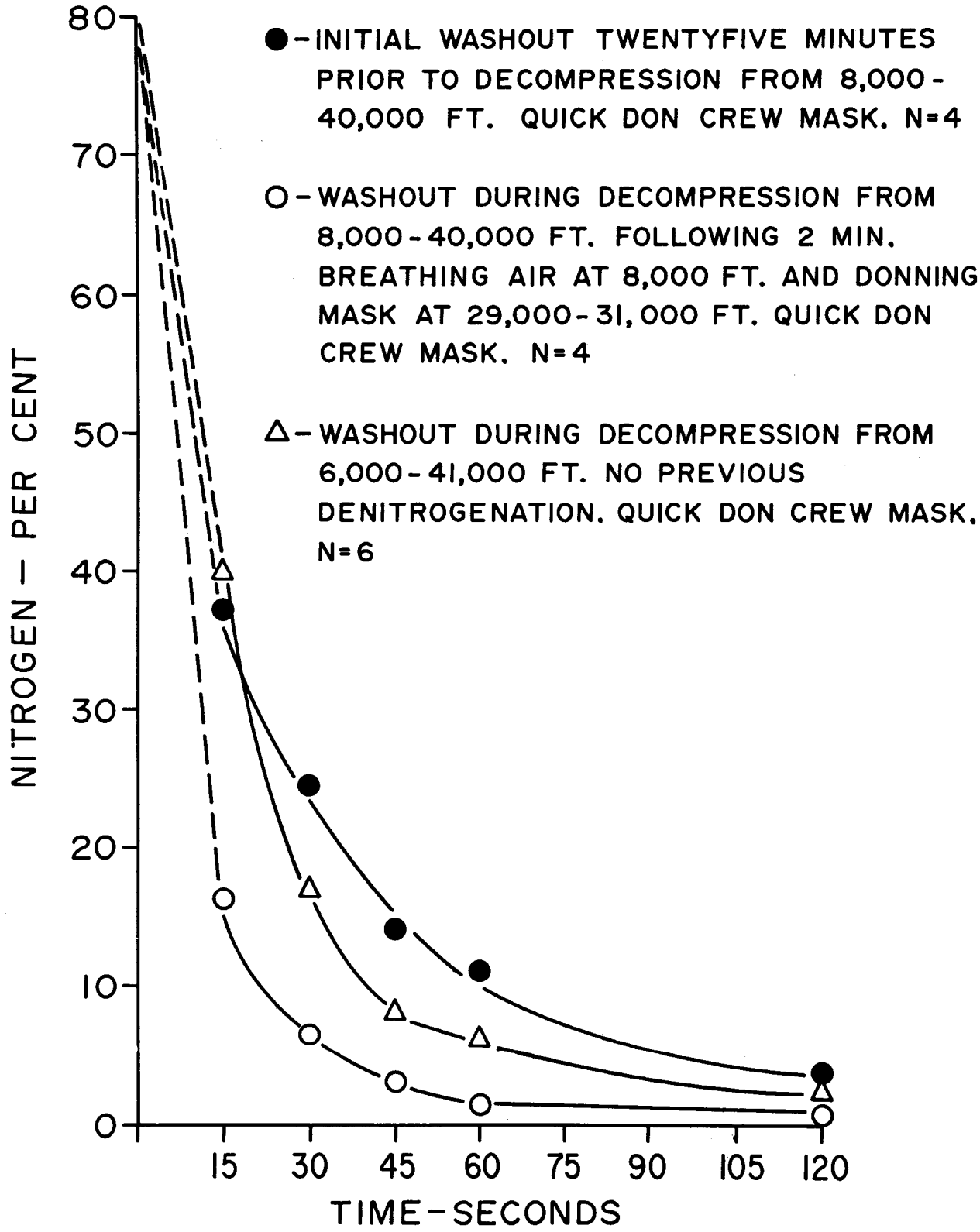

FIGURE 8. Respiratory nitrogen washout of subjects at ground level (1,273 feet) compared to subsequent washout during decompression following 2 minutes of air breathing. The third curve of respiratory nitrogen washout during decompression with no prior denitrogenation was obtained from a prior, unpublished evaluation of a quick don crew mask.