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Supply of Oxygen for High Altitude Flying

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Report on

Supply of Oxygen for High Altitude Flying

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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ABSTRACT

This report first discusses the methods available for supplying oxygen to aviators flying at high altitudes. The various oxygen sources and apparatus employing them are described, the advantages and disadvantages of each being stressed. Next, the means by which a carrier or tender can supply the oxygen to ship-based planes are discussed. The general conclusion arrived at is that owing to the lack of essential data and to the rapidity of advance of Naval aviation, no clearcut decision can be made at present as to the best oxygen methods for Naval use.

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AUTHORIZATION

1. This report was requested by the Bureau of Aeronautics letter, reference (a). Other pertinent correspondence is given as references (b) and (c).

- References: (a) BuAero.conf.ltr. Aer-E-252-SG F49-1 of 17 December 1936.
(b) BuAero. Intrabureau Restricted Memo. Aer-E-252-AQ F49-1 OVL/MVL of 6 June 1935.
(c) BuAero. Intrabureau Memo. Aer-E-252-RL QB(71)F49-1 of 16 June 1936.

The "confidential" status of this report is necessitated by reference herein to confidential problems under the cognizance of other Bureaus.

STATEMENT OF PROBLEM

2. Above certain altitudes, a human being acclimated to normal atmospheric pressure is affected by lack of oxygen unless provision is made to supply air or oxygen artificially. High-altitude planes must therefore carry some source of oxygen for their personnel. For ship-based aircraft, this oxygen source must be supplied by the carrier or tender. This report appraises the available sources of oxygen for aircraft and the methods for supplying these oxygen sources from carriers and tenders.

KNOWN FACTS BEARING ON THE PROBLEM

Historical

3. During the later stages of the World War, the development of combat flying had already reached the point where altitudes at which the pilots required oxygen were often reached. Crude apparatus to supply this was hurriedly developed. Since that time, all of the major air powers have studied the physiology of high-altitude flying and have developed many forms of oxygen apparatus. Resumes of the earlier developments are given in the bibliography.

4. The physiological factors governing the behavior of pilots under conditions existing at high altitudes are none too well known; but research on these is being continuously done throughout the world. Several of the references in the bibliography deal extensively with these physiological factors.

5. For the oxygen consumption calculations in this report, a normal healthy man acclimated to sea level conditions will be taken as the standard. The amount of oxygen consumed by his body is governed largely by the amount of carbon dioxide liberated in his lungs. When seated at rest, this amounts to about 0.70 cu.ft. of carbon dioxide per man per hour. The amount of oxygen necessary to liberate this amount of carbon dioxide varies with the nature of the food which is eaten. With a normal diet, the respiratory quotient, that is to say, the ratio of the volume of carbon dioxide to the volume of

CONCLUSIONS.

(a) The following insulating compounds were found unsuitable as water-proofing material for multi-layer radio frequency inductances:

Bakelite varnish No. 6049.
Bakelite varnish No. 6653.
Insulex No. 33.
Insulex No. 67.
Liquid Crolite Super-Quartz.
National Company Coil Dope.
Q-Max No. 3.
Q-Max No. 4.
Solaroid air-drying varnish.

(b) The following waxes were found suitable for this purpose:

Q-Max wax.
Refined high-melting-point paraffin.
Superla wax.

(c) The suitability of a material as a water-proofing coating for inductances for general radio frequency use should be determined by tests on multi-layer coils which approximate, in depth of winding and coil capacity, the larger coils which it may be desired to protect against high humidities. Such a coil is described in this report under "Recommendations."

oxygen consumed, is equal to about 0.82; therefore, about 0.85 cu.ft. of oxygen per man per hour is required. This consumption is little affected by altitude, but is increased by muscular activity.

6. Such a normal individual acclimated to sea level conditions, when on a flight to high altitudes, will require some source of oxygen above 12,000 to 15,000 feet. Lacking this, the effects of oxygen deficiency will ensue. Oxygen want is very insidious and may appear quite unexpectedly with the pilot thinking himself perfectly well and happy but actually on the verge of collapse. To quote an English authority, Major C.J. Stewart, "It is important to realize, however, that the dulling of perception and judgment begins in most people at 12,000 ft. to 15,000 ft. The pilot himself may not be, and usually is not, aware of it. On the contrary, he very probably has a somewhat exalted sense of confidence. He is, in fact, somewhat like those bibulous wits who imagine they are very clever, whereas to the onlooker their lack of judgment and coordination is painfully apparent."

7. Given an adequate supply of oxygen and sufficient clothing to keep warm, the pilot in an open cockpit plane can go up to a critical region of about 42,000 - 45,000 feet, above which physiological reactions caused by the low pressure on the outside of his body may induce collapse. Above this, some form of pressure-tight cabin or other means of maintaining a pressure on the pilot's body must be employed. (It is true that the Italian aviator, Commendatore Donati, went to 47,360 feet in an open-cockpit plane. But he was especially trained in high-altitude flying and in spite of this almost collapsed.) Plate 1 is the familiar pressure-altitude curve based on the U.S. standard atmosphere and shows these critical regions.

8. Whatever source of oxygen for respiration is provided, there are two basic methods of employing it:

- (a) The inhalation cycle. In this, the oxygen is inhaled from the source of supply and the products are breathed out into the atmosphere surrounding the pilot.
- (b) The re-breathing cycle. Here, the oxygen is inhaled from the source and the products of respiration are exhaled through the chemical purifying agents which remove the water and carbon dioxide expired and return the unused oxygen to the supply. The Navy submarine escape lung is an excellent example of the re-breathing cycle. The data given above for the net oxygen consumption of 0.85 cu.ft. per hour is the amount of oxygen required for a perfect re-breathing cycle.

9. Physiological studies show that the re-breathing cycle is far more economical of oxygen. A normal man seated at rest breathes about 16 times per minute and at low altitudes each breath takes in about 0.018 cubic feet, a total inspiration of about 17 cubic feet per hour. If he is breathing pure oxygen, the oxygen supply must be at this rate. With increasing altitude, the depth of breathing tends to increase, but as the pressure decreases, the volume of the oxygen breathed measured at sea level pressure would tend to decrease. (Since only 0.85 cubic feet per

hour of oxygen is actually consumed by the body, the wastage with the inhalation cycle is great.) Current practice in airplane oxygen supply is not to breathe pure oxygen at all altitudes, but to permit the pilot to breathe in air at all altitudes and to mix with the air going into his lungs sufficient oxygen to make up the oxygen deficiency in the low pressure air. In Plate 2 a comparison of oxygen requirements of these various systems is given. The lower curves (1) represent the oxygen required by a man with a perfect re-breathing system; the upper curves (2) are estimates of the oxygen delivery of a system in which he breathes pure oxygen at all altitudes; and curve 3 shows the British Air Ministry standard delivery for a system supplying oxygen to make up the oxygen deficiency in the low pressure air breathed. This last curve includes an allowance for the wastefulness of this system and for considerable activity on the part of the pilot. The character of curves 1 and 2 at high altitudes is uncertain and is so indicated by the dotted lines. (In all gas volume data given in this report, the volume which the gas would occupy if it were compressed to sea level pressures is given unless a specific statement to the contrary is made.)

Definition of Quantity of Oxygen Required

10. It is suggested that the quantity of oxygen to be carried aboard a plane be specified as follows: The plane shall carry sufficient oxygen to supply its occupants during a flight in which the plane climbs at its maximum rate to its service ceiling, flies at that altitude until its gasoline supply is practically exhausted, and then returns to a high pressure level.

11. In the calculations below, a plane carrying 150 gallons of gasoline consumed at a rate of 30 gallons per hour will be assumed. The oxygen storage for one man for five hours at high altitude will therefore be computed. The nature of the oxygen consumption curves (Plate 2) makes it difficult to make a rational assumption as to the probable rate of use of oxygen. A reasonable compromise of 1 liter (= 0.035 cubic feet) per minute for the re-breathing cycle and 5 liters (= 0.18 cubic feet) per minute for the inhalation cycle will therefore be assumed. For a five hour flight these figures correspond to 10.5 cubic feet total and 53 cubic feet total, respectively.

OXYGEN SOURCES ON THE PLANE

12. The characteristics of the source of oxygen for supplying high altitude planes will have to be a compromise between the following desiderata:

- (a) Operation. It must be positive in operation. Material failure on a plane, even serious structural and power plant failure, usually permits the pilot either safely to land or to bail out. But failure of the oxygen supply leads to unconsciousness or impairment of manual function which may result in death from crashing or from suffocation. Several recent record flights - for example, those of Howard Hughes, Squadron Leader Swain and Commandatore Donati - have been characterized by failure of the oxygen supply with almost disastrous consequences. If positive operation under all conditions cannot be insured, some emergency provision for oxygen supply must

be made. The apparatus should be simple and preferably automatic, as the pilot is preoccupied with his other duties. If possible, it should be governed by the demand of the lungs. The system must function continuously, whatever the altitude of the plane; vibration must not affect it.

- (b) Maintenance. The oxygen supply should be quickly replenishable or replaceable and should be simple to maintain and repair.
- (c) Constraint. The equipment should interfere as little as possible with the movements of the pilot and with his vision, hearing and speech. Machine gunners (operating a free gun) must be especially free to move rapidly and must have a wide field of view.
- (d) Weight. The weight of the oxygen equipment must be as low as possible compatible with the necessity for positive operation and other desired characteristics.
- (e) Space. The space required should be as low as possible. The space occupied should, if feasible, be space which would remain otherwise wasted, as in wings, aft in the fuselage, under seats, etc.
- (f) Composition Control. There is considerable evidence to show that prolonged breathing of pure oxygen may be undesirable. Small percentages of carbon dioxide are apparently advantageous. In his record altitude flight Com. Donati used an oxygen-carbon dioxide mixture as a result of the conviction of the Italian aviation medical authorities that carbon dioxide was necessary in oxygen for use above 30,000 - 35,000 feet. Breathing of dry oxygen dries up the mucous membranes, with resultant discomfort and possible impairment of clarity of speech. It may therefore be necessary to employ apparatus by which carbon dioxide and water vapor may be added to the inspired oxygen, or experience may prove other compositions, such as oxygen-enriched air, to be more satisfactory. Ability to control the composition of the inspired oxygen is therefore desirable.
- (g) Economy of Oxygen. The system should be economical in its consumption of oxygen.
- (h) Temperature Effects. The system must be insensitive to great changes in ambient temperature. Any moving parts or connecting tubes must not cease functioning by becoming clogged with ice. The oxygen must reach the pilot at a temperature close to body temperature.
- (i) Altitude Effects. The apparatus must function properly at all altitudes and with rapid change in altitude.
- (j) Health Hazard. The oxygen source must not constitute a hazard to the health of the pilot, as from contamination by chemicals or by carbon monoxide from the engine exhaust. Experience has

shown that breathing very cold oxygen, as from liquid oxygen sources, may contract the metallic fillings in teeth and result in their loss. The efficiency of the personnel, especially the pilot, must be kept at a maximum.

(k) Adaptation to Plane Type. The system must be adapted to the specific type of plane on which it is to be used. Thus pursuit planes for acrobatic and flying and dive bombers require apparatus which will function in attitudes and under accelerations which make impossible the use of equipment which would be satisfactory on patrol planes.

13. There are three general ways for carrying the required oxygen on board a high altitude airplane:

- (1) Gaseous oxygen { as air
as pure oxygen
- (2) Liquid oxygen.
- (3) Oxygen in chemical form.

14. One apparent method of supplying air to the pilot is to have a mask supercharged to about 1 atm. as by the engine super-charger. This method is of very limited application, as at any altitude there would be an excess pressure within the lungs above that on the outside of the body. Experiment (by the Experimental Diving Unit, Washington Navy Yard) proves that the body can withstand such a pressure difference only when it is not greater than a very few pounds per square inch.

15. Two methods have been suggested for using air. In the first, the plane is provided with a sealed cabin which is maintained at a pressure corresponding to an altitude of 12,000 feet or less by means of the engine or other super-chargers. Officials of transport lines already foresee the time when transport planes will be designed with sealed cabins. The TWA, and the Douglas and Martin Companies are experimenting with this type of construction as is the U.S. Army Air Corps. The decision to use super-charged cabins for transport planes rests upon considerations of passenger comfort and psychology which are not primary requirements in Naval and military planes. In military and Naval planes, where the sealed cabin might be punctured by machine gun bullets and the "airtight integrity" of the plane thereby destroyed, it is questionable if this system will be employed except in planes which have to go above the critical height of 42,000 feet.

16. The super-charged cabin system has many advantages. It is automatic and reasonably positive in operation, does not constrain the pilot (except that it limits his vision), is unaffected by altitude, keeps the pilot warm by the adiabatic heating and requires no additional space. The outstanding advantage of this method is that it introduces few new and little understood physiological and psychological factors as the pilot remains in an air-environment to which he is accustomed. The chief disadvantages of the system are the liability to puncture by machine-gun bullets and the extra structural weight to construct an airtight cockpit. Against the additional weight required, allowance must be made, however, for additional weight which would be demanded by other systems and for additional equipment required in high-altitude flying. Thus, in high-altitude planes, some provision, involving additional weight, may be

required to prevent high-voltage discharge in the radio equipment. With open cockpit planes this would require equipment which would not be necessary with sealed cockpit planes. Similarly, the open cockpit plane requires some type of heating with a weight charge against the plane either from the heater or from the electrical power consumed.

17. Alternatively, the pilot and other personnel can be supplied with an airtight suit, virtually a diver's suit, each connected to the supercharger so that a pressure of roughly 1 ata. is maintained within it. Such a suit was employed by the late Wiley Post and by the English flier Squadron Leader Swain recently in making the world's altitude record. A suit of this type is heavy and is a serious charge against the weight of a high-altitude plane and hence at present may not be considered feasible for Naval use. However, should the development of chemical warfare require that Naval aviators be provided with chemically-resistant suits, such a suit could readily be designed to withstand the required pressure and be used to supply air for breathing. The additional weight would be a charge against chemical warfare defense rather than against the oxygen source. The "diver's suit" system has most of the advantages and disadvantages of the sealed cabin system. Its chief disadvantages are the weight required and the restriction of movement. It is not adapted to patrol and other multi-passenger planes.

18. Plate 3 shows the "diver's suit" used by Squadron Leader Swain in making the world record altitude flight of 49,967 feet. This suit, of rubberized fabric, large enough to fit over the thick normal flying clothes, was developed for the British Air Ministry as a result of work by the famous physiologist, the late Prof. J.S. Haldane. Some of the details of this suit have been kept confidential by the Air Ministry, but it is known that it includes a helmet with the large curved double window shown and that the re-breathing cycle was employed. In this particular flight the suit was not supercharged with air but instead the suit was inflated with oxygen. Oxygen was fed into the system through a small injector which produced a rapid circulation of gas through the system. From this injector, the gas passed through the flexible tube entering the helmet and swept across the face, thence through an outlet and down a flexible tube to a canister containing chemicals to absorb the carbon dioxide and moisture from the breath. From the canister outlet the pure oxygen was re-circulated through the system. In such suits several individuals, including Squadron Leader Swain, have been taken to "altitudes" of 80,000 feet in a low pressure chamber without undue discomfort. Flight tests showed the vision and control to be satisfactory. The suit weighs 30 pounds, while auxiliary oxygen apparatus on the record flight weighed 40 pounds. (The plane was especially constructed for high-altitude research.)

19. Since all of these methods of employing air from a supercharger are of doubtful immediate utility, recourse must be had to the use of oxygen in one of the several forms given above - gaseous oxygen, liquid oxygen, or chemical sources.

Gaseous Oxygen

20. Three methods have been suggested for carrying oxygen gas aboard planes. In the first, the plane has a sealed or semi-airtight cabin, the air in which is enriched with pure oxygen and kept at approximately the

pressure corresponding to the plane's altitude by leakage of air and oxygen from within as the altitude increases, a small excess pressure being maintained. This system is somewhat more flexible in application than the sealed cabin using air from the supercharger. The additional structural weight required would be much less as absolute airtightness would not be necessary. Puncturing by machine gun bullets would not be as disastrous as with the air filled cabin (assuming the plane to be made of fireproof materials). The outstanding disadvantage of this system is its enormous consumption of oxygen which probably makes it impracticable for military planes. Additional oxygen supply of some one of the other forms considered would have to be provided.

21. The foregoing systems have all had a feature in common of placing the entire body of the pilot in a controlled environment. Lacking these, recourse must be made to methods wherein the oxygen is supplied by mouthpiece or mask. It should be reiterated, however, that as higher altitudes are attained, as by planes reaching 42,000 feet or more, it will be necessary to use some one of the supercharger methods, as the body cannot function properly under the extremely low pressures of these high altitudes even if abundant oxygen is provided.

22. Balloons. The second method of carrying oxygen gas is to use a distensible balloon, as shown in Plate 4. In this, B is the fabric balloon which is filled to about half its capacity at sea level with oxygen before the flight. As the altitude of the plane increases, the balloon distends with decreasing external pressure. From this balloon, a flexible tube connects the pilot and mask. A smaller emergency supply can also be carried as in D under the pilot's seat. If the re-breathing cycle is used, a second tube leading through the purifying canister C returns the unused oxygen to the balloon. This balloon system is probably the lightest available method of carrying oxygen. It was used by the French during the World War but abandoned because it was found that incendiary bullets ignited the balloon and the wooden fuselage of the plane. Whether this objection obtains with modern planes at high altitudes is difficult to decide. The advantages of the balloon system are:

- (a) Operation. This system should be positive in operation. Modern balloon fabric is very strong, retains its flexibility at low temperatures, and is very impervious to gases. There are few moving parts to get out of order and operation is entirely automatic. As the balloon is light in mass, it is little affected by acceleration and change of attitude of the plane. The system can use large connecting tubes which could not clog up with moisture from the breath.
- (b) Maintenance. The balloon can quickly be refilled in the plane and is simple to maintain and repair.
- (c) Constraint. A properly designed mask and flexible connecting tube would minimize constraint.
- (d) Weight. Very low. On the basis of French data a system for use with the re-breathing cycle would weigh about 3.0 lbs.; with the inhalation cycle, about 12 lbs.

- (e) Composition Control. With the inhalation cycle, any desired composition of gas could be used (except that the water content would be limited by the ambient temperature).
- (f) Economy of Oxygen. The balloon system is economical of oxygen. The oxygen remaining in the bag after a flight would not be wasted.
- (g) Altitude Effects. This system is self-compensating to change in altitude.
- (h) Health Hazard. The health hazards are a minimum.
- (i) Adaptation to Plane Type. This method is adapted to most types of planes.

23. The disadvantages of the balloon method are that the balloon can be punctured by machine gun bullets and that the space required is very large. The amount of space is, of course, much smaller with the re-breathing cycle. The volume required for the re-breathing system would be 10.5 cubic feet at sea level, expanding to about 30 cubic feet at 30,000 feet.

24. Compressed Gas. Third, gaseous oxygen can be stored under pressure in metal pressure vessels. This system has been used by all air forces. From a valve on the pressure vessel, a pressure tube leads to the reducing valve from which a low pressure line leads to the pilot's mask. This pressure system is best adapted to use with the inhalation cycle; if the re-breathing cycle is used, some low pressure reservoir must be employed to store the exhaled oxygen. The outstanding deficiency of the pressure system is its weight - the pressure vessel, reducing valve and other auxiliaries being necessarily heavy.

25. A complete compressed gas system using a modified inhalation cycle is shown in Plate 5a. It comprises the compressed oxygen cylinder A, the pressure gauge C to measure the cylinders content, the reducing valve and regulator B, and the flowmeter F which indicates the amount of oxygen flowing into the mask H. The cylinder in British practice is fabricated from a special alloy steel and can be punctured by a machine gun bullet with impunity when filled to the fully charged pressure of 1800 p.s.i. The mask H has louvres through which the pilot breathes air. As the altitude increases, he adjusts the regulator E to permit oxygen to flow into the mask at a sufficient rate as to supply the oxygen deficiency in the air which he breathes. In more recent systems, the regulator B is automatic, the oxygen delivery being controlled by a barometric-pressure valve. The U.S. Army standard regulator is a highly-perfected automatic one.

26. German practice differs in important details from American and British. With the system just considered, oxygen is flowing into the mask continuously. But since during an interval of one minute, the pilot is inhaling for a time totaling only about 23 seconds, much of the oxygen flows out through the louvres in the mask during the other 37 seconds and is wasted. To diminish this waste, the German apparatus bleeds the oxygen from the pressure cylinder into a balloonet from which it is drawn by the lungs on the next inhalation. Such a system is shown in Plate 6. From the flask A, the oxygen passes through the valve B into the balloonet C. As the low-pressure oxygen is drawn from the balloonet, it collapses and the

air-pressure acting upon it actuates the valve B by means of the lever system D. The mask E contains an air-inlet valve F and an exhaling-valve G. With this system, the flow of oxygen is controlled by the demand of the lungs.

27. A German re-breathing system is shown in Plate 7. Oxygen from the flask A bleeds through the valve system B into the balloonet C. When the pilot inhales, this low-pressure supply passes through the check valve D into the mask E. Exhalation forces the gases through the check valve F and thence through the chemical purifier G which removes the carbon dioxide and water. The unused oxygen returns to the balloonet C.

28. Typical German equipment is illustrated in Plate 8. At the left is a two-man inhalation system of the type just described but fitted with electric heaters to heat the inspired oxygen; in the center is a complete flying outfit with a barometric-pressure governed oxygen regulator (and at the right is a typical liquid-oxygen supply).

29. The advantages of the compressed-gas system are:

- (a) Operation. In principle, the operation of this system should be positive and practically automatic and experience shows that it is so if properly designed and carefully manufactured. Experienced pilots, however, have had so many failures with this system that they invariably carry an alternative emergency supply. The system is not affected by the altitude of the plane.
- (b) Maintenance. The oxygen tanks are readily replaceable in the plane and can be quickly refilled on the carrier or at the base.
- (c) Constraint. With good masks, little constraint is caused.
- (d) Space. Low.
- (e) Composition Control. Any composition of gas can be used except that the gas must be absolutely dry to prevent freezing of the valves.
- (f) Economy of Oxygen. The system is very economical of oxygen. Any gas remaining after a flight is not wasted.
- (g) Temperature Effects. This system is not affected by temperature, if properly designed.
- (h) Altitude. Unaffected by altitude.
- (i) Health Hazard. Small.
- (j) Adaptation to Plane Types. This system is adapted to all types of planes.

30. The disadvantages are:

- (a) Operation. Unfortunately, service experience gives a record of too frequent malfunctioning of the valves, regulators and other parts of this system.

- (b) Weight. With the re-breathing cycle, the oxygen cylinder alone for a five-hour flight would weigh about 5 lbs.; for the inhalation cycle, about 25 lbs., on the basis of British Air Ministry data. These weights do not include the regulator and flowmeter. With the necessary auxiliaries, the re-breathing system would then weigh about 9 lbs., the inhalation system about 28 lbs.

Liquid Oxygen

31. Liquid oxygen systems have been experimented with widely by the major air powers. In this system, liquid oxygen is stored in a vacuum vessel of the metal thermos bottle type from which a low pressure tube connects with the pilot's mask. The supply is regulated by boiling the liquid by supplying heat at the correct rate. The liquid oxygen system is best adapted for use with the inhalation cycle; if the re-breathing cycle is used, some low pressure gas storage reservoir must be fitted for the exhaled oxygen. The chief advantage of the liquid oxygen system is its low weight; and its outstanding difficulty is to design the equipment to insure proper regulation and so that it will function properly in inverted and acrobatic flight. The following description of the British liquid oxygen system shown in Plate 5b is taken verbatim from C.J. Stewart "Aircraft Instruments":

"Owing to the low critical temperature of oxygen it is impracticable to store it in the liquid form except at atmospheric pressure in double walled vacuum vessels. Metallic vessels, generally spherical in shape, are used on aircraft on account of their robustness and from considerations of heat transfer. In the design of such vessels consideration must be given to the transfer of heat by radiation across the vacuum space, convection in the residual gas in the vacuum space, and conduction from the metallic connection at the neck. To reduce the heat transfer due to the neck, the latter is made long, thin, of small bore and of a metal of relatively low thermal conductivity. The transfer of heat by convection and conduction across the vacuum space is reduced by the provision of an absorbent material cooled to the temperature of the contained liquid to maintain a high degree of vacuum. Radiation heat losses are minimised by highly polishing the surfaces of the walls adjacent to the vacuum space.

"A modern liquid oxygen vaporiser is shown diagrammatically in Plate 9. The vaporiser consists of two parts - the storage vessel A and the evaporator B, which is screwed thereto. The evaporator comprises a long syphon tube C, whose lower end dips into the liquid D in the storage vessel, and whose upper end is connected to the lowest section E of a flash boiler. The latter, which surrounds the neck of the storage vessel, is cylindrical in shape and is provided with internal baffle plates F. An outlet G at the top of the evaporator is connected to the needle delivery valve of a control fitting H. A second outlet J in the portion which screws on the neck of the storage vessel is connected to the spring-loaded, pressure-release valve K of the control fitting.

"From the diagram it will be observed that there are two circuits: (i) the pressure circuit, comprising the space in the storage vessel above the surface of the liquid connected to a pressure gauge and release valve, and (ii) the delivery circuit comprising the syphon tube connected through the flash boiler to a delivery control valve. The liquid evaporates slowly, building up a pressure, whose value will be indicated on the pressure gauge; if, when this pressure has built up sufficiently, the delivery valve be opened, a reduction of pressure occurs in the flash boiler, and the pressure on the surface of the liquid forces a small quantity up the syphon tube into the flash boiler, where it vaporises instantly. This evaporation tends to equalise the pressure in the flash boiler and in the storage vessel, so that the flow of liquid up the syphon tube ceases. When the gas has passed through the delivery valve the pressure in the flash boiler decreases until eventually, more liquid is forced up the syphon tube. Further opening of the delivery valve accelerates the flow of liquid, with a consequent increase in the delivery of gas. The production and maintenance of an adequate pressure in the storage vessel is a matter of importance,

.....

"On climbing, the atmospheric pressure decreases, and so the pressure release valve will open and release some of the pressure in the vaporiser vessel; but this reduction of pressure in the vaporiser vessel will lower the boiling point, causing the liquid to evaporate more readily, thus tending to increase the pressure. The net decrease in the pressure in the vaporiser vessel, however, since the pressure release valve cannot release the gas quickly enough on a fast climbing machine, is not so great as the reduction in atmospheric pressure....."

"On descending, the atmospheric pressure increases, and thus the pressure release valve tends to close, the pressure in the vaporiser vessel remaining unchanged except in so far as it is increased by normal evaporation of the liquid, which of course decreases as the pressure in the vaporiser vessel increases. The net result on descent is, therefore, that the pressure in the vaporiser vessel increases only slightly whilst the atmospheric pressure increases rapidly....."

32. In early French liquid-oxygen systems, the heat required to boil the liquid oxygen was supplied by electric immersion heaters and thus was readily controllable by the pilot.

33. The advantages of the liquid oxygen system are:

- (a) Weight. A liquid oxygen re-breathing system would weigh about five pounds; an inhalation system, about fifteen pounds.
- (b) Space. The space required is roughly the same as that in compressed gas systems.

(c) Temperature Effects. Owing to the low boiling point of the liquid oxygen, ordinary temperature changes have little effect.

(d) Adaptation to Plane Type. This system is adapted to any type of plane except acrobatic pursuit planes and dive bombers. It is especially good for supplying oxygen to closed cabin transport or other large planes.

33. The disadvantages:

(a) Operation. Actual service experience with liquid-oxygen systems has proved disappointing, owing chiefly to maintenance and supply difficulties.

(b) Maintenance. Since the liquid oxygen is constantly boiling away, the liquid-oxygen system must be put aboard the plane just before a flight. Great care must be used to keep the liquid containers free from water, which is not easy to do.

(c) Composition Control. The liquid system can only deliver pure dry oxygen.

(d) Economy. The system is very uneconomical of oxygen. Transfer losses in filling the plane's thermos bottles are high and the liquid oxygen aboard the plane evaporates rapidly. Any oxygen remaining after a flight is wasted.

(e) Altitude Effects. A very serious drawback to the liquid oxygen system is the change in the boiling point of the oxygen with altitude. As the altitude of the plane increases, the lowering of the boiling point causes oxygen to boil away at a high rate. But if the plane is descending rapidly, the increased pressure prevents the oxygen from boiling and therefore starves the pilot unless rapid adjustment of the heat input is made.

Oxygen in Chemical Form

34. Chemical sources of oxygen have been widely tested, especially in Germany and Italy. Chemical sources employ some substance which can liberate oxygen by a chemical reaction which can be initiated by the pilot. Chiefly, these sources have employed activated sodium peroxide, although other chemicals containing perchlorates have been used. Three chemical sources will be considered:

35. Pyrogenic Materials. A number of chemical substances which give off oxygen when heated are known. Weight considerations limit their number and of these the perchlorates are probably the best. There is available in Germany an oxygen source comprising a composition which, when ignited electrically, gives off oxygen continuously until the chemicals are expended. The chief advantages of this system are that it is automatic in operation and light in weight; its chief disadvantage is that it cannot be controlled. Its advantages are:

(a) Operation. This oxygen source, when once started, continues automatically and functions independently of the attitude of the plane.

- (b) Maintenance. This system is quickly replaceable and simple to maintain.
- (c) Constraint. The equipment would interfere little with the pilot.
- (d) Weight. The weight would be low.
- (e) Space. Small.
- (f) Temperature Effects. This system functions at all temperatures and delivers warm oxygen to the pilot's mask.
- (g) Altitude Effects. The oxygen generation is independent of altitude.
- (h) Adaptation to Plane Type. This system is adaptable to all types of planes.

36. The disadvantages of the pyrogenic chemicals are:

- (a) Economy of Oxygen. Once the oxygen reaction is initiated, it can be neither stopped nor can its rate be controlled. The chemical composition must therefore be such as to produce oxygen at the maximum rate which may be demanded and it is therefore uneconomical of oxygen.
- (b) Composition control. These chemicals deliver pure oxygen and the composition cannot be controlled.

37. Alkali Metal Peroxides. The alkali metal peroxides, of which sodium peroxide so widely used in Germany is an example, are solid substances which generate oxygen when acted upon by water or carbon dioxide. For use as a source of oxygen for respiration, the water and carbon dioxide are supplied from the expired breath. The outstanding advantage of these chemicals as oxygen sources is the low weight. This factor makes it possible to supply equipment which the pilot can carry on his chest or back - he would then have an oxygen source even if forced to bail out of the plane. A unique and very important consequence of this feature of the solid chemical sources is the possibility of using them in conjunction with chemical warfare defense equipment. With such an oxygen source, aviators wearing hermetically sealed chemically resistant suits could, with impunity, leave the ready room (assumed to be chemical-proof), get in their planes and fly off the carrier even if the flight deck and all the planes on it had been sprayed with gas. Other advantages are:

- (a) Operation. This system would be positive in operation and practically automatic. The apparatus would be simple and not apt to get out of order.
- (b) Maintenance. The oxygen source would be quickly replaceable and there would be practically no maintenance and repair.
- (c) Constraint. The equipment would interfere little with the pilot and is especially adaptable to gunners operating free machine guns.

- (d) Weight. A re-breathing system for a 5-hour flight would weigh about 4 pounds.
- (e) Space. The space required would be very small.
- (f) Economy of Oxygen. This system is very economical of oxygen.
- (g) Temperature Effects. Some of these chemicals are insensitive to change in temperature. The chemical reaction generating the oxygen gives off heat which warms the oxygen delivered to the mask.
- (h) Altitude Effects. The apparatus would function independent of altitude.
- (i) Adaptation to Plane Type. This system is adaptable to any type of plane.

38. Its disadvantages are:

- (a) Composition Control. These sources generate pure oxygen and the composition could be controlled only with difficulty.
- (b) Health Hazard. A possible health hazard from breathing powdered chemical exists but can be overcome with suitable filters.

39. Hydrogen Peroxide. Hydrogen peroxide is a chemical available commercially in water solutions containing 30% by weight of hydrogen peroxide, and it can be obtained of 50% strength on special order. These solutions are somewhat unstable in storage but can be stored for several months without serious loss. By the action of simple catalysts, oxygen is readily liberated from the solution. The chief advantage of hydrogen peroxide as a source of oxygen is its light weight; its chief disadvantage is difficulty in designing suitable apparatus for using it. Other advantages:

- (a) Maintenance. The apparatus would be easy to refill and to maintain, requiring only periodic cleaning.
- (b) Constraint. The equipment would interfere but little with the pilot.
- (c) Weight. A re-breathing system would weigh about 6 pounds, an inhalation system about 22 pounds.
- (d) Space. Space required would be small.
- (e) Economy. This system would be economical of oxygen.

The disadvantages are:

- (a) Operation. It would be difficult to make an automatic apparatus requiring no attention from the pilot. Owing to the use of a liquid source of oxygen, it would be difficult to make equipment which would function whatever the attitude of the plane, especially for acrobatic and dive-bombing planes.

- (b) Temperature Effects. There would be some danger of the equipment clogging up by the freezing of water generated by the reaction.
- (c) Composition Control. Pure oxygen is generated and the composition therefore could not be controlled; the oxygen would contain water vapor.
- (d) Adaptation to Plane Type. The hydrogen peroxide system is chiefly adaptable to large patrol planes and is not adaptable to small pursuit ships.

Chemical Purifying Agents for the Re-Breathing Cycle

40. The re-breathing cycle requires the use of some chemical substance or agent to remove the carbon dioxide and water vapor from the exhaled breath so that only pure oxygen is returned to the main supply. The agent which has heretofore been used is soda-lime, which is widely employed in chemical warfare gas masks and was formerly used in submarine air purification. Soda-lime has the very serious deficiency of not functioning properly at low temperatures. This fact, which is not generally known outside our Navy, was established by experiments at this Laboratory which proved that soda-lime does not effectively absorb carbon dioxide at temperatures below about 40 degrees. It is quite probable that failure to appreciate this fact has had disastrous consequences which were ascribed to other factors. Thus in the world's altitude record flight of Squadron Leader Swain, the carbon dioxide canister (the nature of the chemical in which has not been disclosed) failed to function properly with nearly disastrous consequences. After the flight, it was found to be in perfect condition. These facts are explicable on the assumption that soda-lime was the carbon dioxide absorber. The only known carbon dioxide absorbent which will function properly under the wide range of temperatures conditions met in high-altitude flying is the new confidential submarine air-purifying material developed by this Laboratory for the Bureau of Construction and Repair. (In the calculations on re-breathing systems given above, the use of this absorbent was assumed.)

41. The use of this new carbon dioxide absorber for purification in the re-breathing cycle would probably require the use of a water absorber as well. Several new water absorbents have been developed in the past few years but, so far as is known, none have been tested for this use. Among these are silica gel, magnesium perchlorate, etc.

OXYGEN SUPPLY ON THE CARRIER

42. Whatever source of oxygen is chosen for the plane, that oxygen source has to be furnished by the carrier to all ship-based aircraft. On board the carrier, this oxygen source must either be (a) stored or (b) manufactured. Of the oxygen sources described, it is impractical to manufacture the chemical sources aboard ship, hence the chemicals must be stored; the gaseous and liquid oxygen can either be stored or manufactured. The carbon dioxide and water absorbents for re-breathing systems must be stored.

Quantity of Oxygen Required

43. A carrier must be prepared to supply oxygen to all of its planes during a prolonged absence from its base. It must supply relatively small quantities of oxygen daily for long periods and yet be able to supply its complete complement of planes with oxygen for virtually continuous flying over a period of a few days. It is suggested that the oxygen storage requirements of a carrier be defined as follows: A carrier must carry sufficient oxygen to supply its planes as long as the gasoline stored on the carrier lasts; the carrier must be able to supply its full complement of planes in continuous flight for two days.

44. In calculating the oxygen storage requirements below, it will be assumed that the carrier stores 150,000 gallons of gasoline. Assuming a consumption of 30 gallons per hour, this is equivalent to 5,000 hours of flying time. Assuming further an average of two men per plane, 10,000 man hours of total oxygen supply will be required according to the above specifications. With the rebreathing cycle at the assumed rate, this is 21,000 cubic feet of oxygen; with the inhalation cycle 106,000 cubic feet.

Requirements of Ship Oxygen Supply

45. The characteristic of the source of supply of oxygen on the carrier must be a compromise between the following desirable characteristics:

- (a) Weight. The weight of the system should be low.
- (b) Space. The space requirements, especially the deck area taken up, should be low.
- (c) Operation and Maintenance. The system should be simple to operate, maintain and repair.
- (d) Personnel. The system should not require an excessive number of men to operate and maintain and preferably should not require specially trained personnel.
- (e) Power. The system should require as little electric power as possible.
- (f) Safety. The system should be safe to personnel.
- (g) Economy. The system must not be too expensive to operate.
- (h) Stability. Chemical and other sources of oxygen should be stable for periods of several months.

STORAGE METHODS

Gaseous Oxygen

46. Oxygen gas could be stored aboard a carrier in steel cylinders under high pressure. Considerations of economy and ease of procurement would probably dictate that the standard Navy compressed-gas cylinders be used.

Under a pressure of 1800 p.s.i., these cylinders store about 220 cubic feet of oxygen and weigh about 130 pounds each. Experience aboard submarines shows that leakage of the valves results in loss of oxygen, for which allowance would have to be made. The losses in transfer of this oxygen to the oxygen supply of the planes would be small. Neglecting storage and transfer losses, the total storage would require 95 cylinders totaling 12,400 pounds and occupying a deck space of 54 square feet, assuming the re-breathing cycle to be used on the planes; in addition, 2000 pounds of carbon dioxide absorbent would be needed. With the inhalation cycle, the oxygen storage would require 485 cylinders totaling 63,000 pounds and occupying a deck space of 275 square feet. By using special high-pressure storage vessels these weights could be reduced by as much as 50%. (In addition, a small oxygen compressor to transfer the gas from the large cylinder to the airplane cylinders would have to be provided if the compressed-gas system were used on the planes.) This system of storing oxygen therefore has the following advantages: ease of operation and maintenance; weight and space which are not excessive; economy; and practically no power consumption. The disadvantages are the leakage of the high pressure gas, necessitating extra cylinders to make up for loss, and some danger through having a large number of compressed gas cylinders aboard Naval vessels.

Liquid Oxygen

47. Methods of storing liquid oxygen have been developed extensively for use in shore plants during the past few years. Liquid oxygen is constantly boiling, the losses from typical industrial storage systems amounting to some 3% of oxygen per day. Hence, were liquid oxygen storage used on an airplane carrier which could remain away from its base for a long period, some provision would have to be made for manufacturing liquid oxygen aboard ship to make up this daily loss.

48. The shipboard storage and production of liquid oxygen have been carefully investigated by Dr. R.H. Canfield of this Laboratory in connection with another problem. He obtained a great deal of (commercially confidential) data from the Linde Company. Dr. Canfield considered three possibilities:

- (a) The liquid would be stored at a temperature below the critical temperature and above the critical pressure of the gas. This would require a large storage vessel under a pressure greater than 750 p.s.i. at an artificially maintained temperature below -118°C . (-190°F .)
- (b) The liquid storage would be with very large vacuum-walled vessels.
- (c) The liquid would be stored in large pressure vessels under conditions wherein a compromise is effected between critical and atmospheric conditions.

49. No instance is known of anyone having attempted oxygen storage under condition (a). To do so might not be out of the question on as large a ship as an airplane carrier, though the refrigeration problem would be a serious one. The Linde Company actually uses the third method (c).

The liquid is stored in large (6-foot) spherical pressure vessels at about 600 p.s.i. These vessels are heavily lagged with magnesia insulation on the outside to reduce heat transfer. The heat loss is further reduced owing to the fact that the high pressure raises the boiling point of the oxygen and thereby reduces the temperature drop through the vessel's wall. The oxygen is, of course, boiling continuously and the gas must be bled out of the vessel at a suitable rate. It is understood that the Linde Company is supplying oxygen in this way to large consumers, transferring at the customer's plant from the pressure vessel, carried by a Linde truck, to special storage vessels forming part of the customer's system. No outstanding advantages of this method for Naval shipboard use are known. It is believed that the Linde Company uses this method in preference to using atmospheric pressure vacuum-walled container chiefly because of the rough treatment incident to transportation by truck.

50. The second method (b) is probably most feasible for Naval shipboard use. Vacuum-walled vessels as large as 200 to 300 liters capacity are known to have been made. Due to their large volume-to-surface ratio, the rate of loss of such containers might be reduced to a fraction of 1% per day, especially if they were provided with auxiliary equipment for renewing or maintaining the vacuum which is their essential feature.

51. The characteristics of the liquid oxygen storage system are:

- (a) Weight. The weight of the system would be fairly low. Making no provision for losses in transferring the liquid oxygen from the main storage reservoir to the airplane apparatus, storage of the 21,000 cubic feet of gaseous oxygen for the re-breathing systems would require the storage of 1,870 pounds of liquid oxygen; a vacuum vessel of this capacity would weigh empty about 1300 pounds, a total weight of 3,170 pounds. With the 600 p.s.i. the total storage weight would be 4,670 pounds. With the inhalation cycle, storage of the 9,450 pounds of liquid oxygen would require a total storage weight of 16,000 pounds with the low pressure storage and 23,650 pounds with the high pressure storage. To these weights, however, must be added the weight of the equipment to replenish the oxygen lost by evaporation from these reservoirs. With the re-breathing system this apparatus would weigh about 1500 pounds; with the inhalation cycle about 6,500 pounds. Against the re-breathing system there must be charged a weight of 2000 pounds of carbon dioxide absorber chemical. The total weights for the re-breathing and inhalation systems would then be 6,700 pounds and 22,500 pounds, respectively, with the low-pressure storage system.
- (b) Space. The space required by any of these liquid oxygen storage vessels would be small.
- (c) Operation and Maintenance. While the storage reservoirs are simple to care for, the liquid oxygen system necessary to make up the daily loss would be somewhat complicated and require specially trained personnel.

- (d) Personnel. Specially trained personnel would be necessary.
- (e) Power. The system would use little electric power.
- (f) Safety. There are some hazards to having large quantities of liquid oxygen aboard a Naval vessel. In contact with organic materials such as linoleum, wood, clothing, etc., liquid oxygen forms a violent explosive. The makeup apparatus is hazardous to operate.
- (g) Economy. Assuming an economical source of oxygen from a shore base, the system would be economical, in spite of the very large transfer and wastage losses for which provision would have to be made.

Chemical Sources

52. The chemicals required for the solid chemical sources of oxygen can be stored in suitable corrosion-resistant, hermetically-sealed containers, as in canisters adapted to be fitted into the plane's oxygen system. The advantages of the solid chemicals for storing oxygen aboard carriers would be: The weight would be low - about 12,000 pounds for the re-breathing cycle; they would occupy little space; no operation, maintenance or power would be required; they would be safe and stable; and no additional personnel would be needed. The chief disadvantages of the chemical sources is their high cost.

53. If hydrogen peroxide solution were used as the oxygen storage, it would be stored in suitable aluminum drums, preferably in the cold storage compartment. Hydrogen peroxide storage would have most of the advantages and disadvantages of the solid chemicals, and the additional disadvantage of being somewhat unstable in storage. For the re-breathing cycle, a storage of 12,000 pounds would be required and with the exhalation cycle 60,000 pounds.

MANUFACTURE ON BOARD CARRIERS

54. Several methods of manufacturing oxygen aboard carriers are available, either as the basic supply or to replenish the oxygen lost from the liquid storage system. These manufacturing systems depend chiefly upon the raw material employed. Thus, oxygen may be manufactured

- (a) From Air. Chemical cyclical processes in which oxygen is extracted from the air by chemicals and regenerated in pure form have been developed, but none of these is feasible for use aboard ship. The only practicable method is to prepare liquid oxygen by well developed liquefaction methods as is so widely done to supply industrial oxygen ashore.
- (b) From Water. Oxygen may be prepared from distilled water by electrolysis with direct current. The hydrogen which is simultaneously generated may either be discarded or used as a fuel under a boiler or in an internal combustion engine. The electrolyzers may operate at atmospheric pressure or under high pressure so that they function as their own high pressure pump.

(c) From Chemicals. Any of the chemicals previously described for oxygen supply aboard the plane might, of course, be used to generate oxygen gas aboard ship but, as a source of liquid or gaseous oxygen, most of these would be too uneconomical. Only hydrogen peroxide could be considered. Oxygen gas could readily be generated from the concentrated peroxide solution by adding appropriate catalytic agents. Such a generator could operate at atmospheric pressure or under high pressure to deliver compressed gas.

55. Manufacture of Liquid Oxygen. To manufacture liquid oxygen from air, carefully purified air is compressed to over 2,000 pounds pressure, cooled by a suitable heat interchanger and then expanded through a nozzle. After the system has been in operation for a few minutes the expanded air is on the point of liquefying and is conducted to a rectifying column similar in principle to ordinary fractional distillation columns. In the Linde system this column consists of a series of pans or shallow vessels arranged one above the other in a cylindrical tower, the condensing vapors rising through perforations in the pans and the condensed liquid spilling over from each pan to the one beneath. (The exact construction of these rectifying towers is guarded with secrecy by most firms.) As the system comes into steady operation, liquid oxygen of over 99% purity is obtained. So far as is known, no liquid oxygen system has ever been installed aboard ship. It should be noted that the operation of the rectifying column, depending as it does on the shallow pans remaining perfectly horizontal, requires that the rectifying column be vertical at all times. In shore installations great pains are taken during erection to insure this. It is evident that a liquid oxygen system of this type would not function aboard ship owing to the rolling and pitching of the vessel. The installation of liquid-oxygen manufacturing systems on carriers would therefore require the development of a rectifying system which would operate efficiently on a rolling and pitching ship. It is believed that a suitable rectifying column could be developed, but this would require extensive laboratory and engineering work. (The Linde Company at one time expressed a willingness to attempt the development of a shipboard liquid-oxygen plant for the Navy if the development costs were appropriated. This offer was later withdrawn. But in a conference with the Bureau of Aeronautics on 19 February 1937, Mr. G.O. Carter of the Linde Company stated that the Company could undertake this development.)

56. The characteristics of a liquid oxygen system to manufacture as required the total need for the oxygen supply of the carrier based planes would be:

(a) Weight. Assuming the plant would have to be of sufficient size to produce the needed supply of oxygen in two days, it would have to weigh 14,000 pounds to supply the re-breathing cycle if operated 24 hours per day. To supply the requirements for the inhalation cycle it would weigh 64,000 pounds under the same assumptions. These figures assume that the shipboard oxygen plant would not differ materially from typical shore installations. Although no shipboard liquid oxygen system has ever been built, this is a reasonable assumption.

- (b) Space. The plants considered would occupy 50 square feet and 200 square feet, respectively.
- (c) Operation and Maintenance. The liquid oxygen plants are not easy to operate, maintain and repair.
- (d) Personnel. Specially trained personnel would be required to operate and maintain the plants. The training and experience of torpedo men and submarine personnel in handling high pressure gases would qualify them for much of this work.
- (e) Power. The power demands for liquid-oxygen production are not excessive. An efficient shore plant consumes about 24 h.p. hours per 1000 cubic feet of oxygen so that the plants considered would consume 500 h.p. hours and 2500 h.p. hours, respectively.
- (f) Safety. The operation of liquid oxygen plants is attended with some hazard.
- (g) Economy. A liquid oxygen plant, assuming it could be built, would be expensive. The development costs for engineering a shipboard system would be high.

57. Electrolytic Oxygen. The manufacture of oxygen by electrolysis is common in shore installations. High pressure electrolyzers have been developed in the past few years. They have been studied in detail by Dr. W.H. Sanders of this Laboratory. In these direct current is passed between corrosion-resisting electrodes immersed in a solution of potassium hydroxide contained in a heavy steel pressure vessel. Hydrogen gas is produced at one electrode, oxygen gas at the other. The characteristics of a shipboard electrolysis system producing oxygen at 1800 pounds p.s.i. would be:

- (a) Weight. Assuming the vessel's power to be 440 volts A.C., a plant of sufficient size to manufacture the required quantity for the re-breathing cycle in 48 hours would weigh 30,000 pounds at a minimum, including the motor generator for converting to low voltage d.c.; for the inhalation cycle the corresponding weight would be 150,000 pounds.
- (b) Space. The high pressure electrolyzers would not occupy much space.
- (c) Operation and Maintenance. The system would be rather simple to operate, maintain and repair.
- (d) Personnel. Few personnel would be required to operate the system, but these should be specially trained.
- (e) Power. The electrolytic production of oxygen requires more power than does the liquefaction method. To produce the quantity for the re-breathing system, 9400 h.p. hours would be consumed, and for the inhalation cycle 47,000 h.p. hours (assuming the hydrogen to be wasted).
- (f) Safety. The electrolytic plant is somewhat hazardous to personnel.

(a) Economy. The plant is not expensive to operate.

Opinions

58. Anyone who reads the technical literature on the subject problem can hardly fail to be impressed by the lack of knowledge about many of the human aspects of high-altitude flight. There seems to be no doubt that the rapid development of the aeronautical sciences will permit the construction of airplanes capable of prolonged flight at high altitudes long before physiological science will give any assurance that pilots can endure such long flights without detriment to their well-being.

59. The need for research in the physiology of high-altitude flying is therefore considered urgent. In making progress in such a field as this where lack of adequate knowledge may lead to disaster, the greatest possible caution is imperative. In advancing the art of deep sea diving, the Bureaus of the Navy Department having cognizance over the several aspects of the work have proceeded cautiously and have done extensive medical and engineering research to determine and minimize the possible hazards to personnel. The expenditure of money which this caution entailed has been fully justified by the results. Yet the total number of Naval deep sea diving personnel involved is only about 250. The Naval aviation personnel who may be called upon for high altitude flight outnumber the divers by about 15 to 1 and the importance of high-altitude research is in about this ratio.

60. As a simple yet striking illustration of the consequences of not appreciating the physiological factors involved, the experience of the IWA experimenters may be cited. As these men were only indirectly concerned with oxygen supply, they used a crude system in their "overweather" flights - breathing cold oxygen from a central liquid-oxygen source. As a result the fillings in their teeth fell out and presumably expensive and painful dental work followed. But the dangers to their teeth, not only from fillings falling out but also from metallic fillings contracting just enough to leak and lead to carious conditions months later, had long before been pointed out in the literature.

61. The dangers to high-altitude flying personnel which are to be foreseen and, if possible, forestalled, involve not only effects on health of a temporary and permanent nature but also physiological and psychological effects which reduce the military efficiency of the personnel.

62. The rapid rates of climb which are being attained with modern high-performance planes make it desirable that the possible dangers to pilots from the "bends" be determined. As is well known, divers who ascend too rapidly may get "the bends", which is caused by the liberation of nitrogen dissolved in the blood. While the amount of nitrogen dissolved in the blood of an aviator is less than that in a diver at any depth, nevertheless, the rapid rates of climb with high-performance planes may be great enough so that there is some danger to a high-altitude flyer. The U.S. Army Air Corps is working on this problem.

63. It is believed that the Bureau should consider the desirability of constructing a low-pressure, low-temperature "altitude chamber" for

making high-altitude studies. Such a chamber could be used for (a) research on the physiology of personnel, (b) test of personnel for high-altitude flying, (c) development of high-altitude apparatus, and (d) test of high-altitude apparatus. The Bureau presumably has considered the desirability of constructing a high-altitude research plane similar to those of the TWA and the British Air Ministry.

Conclusions

64. From the above discussion the following conclusions are drawn:

- (a) In many instances no unambiguous conclusions about the merit of oxygen sources for Naval use can be drawn because the necessary data are lacking.
- (b) There is a lack of physiological data on high-altitude flight.
- (c) The need for high-altitude research is urgent.
- (d) Some source of oxygen is necessary in flights above 12,000 - 15,000 feet.
- (e) For flights above 42,000 - 45,000 feet, some super-charged pilot enclosure is needed.
- (f) Re-breathing systems are more economical of oxygen and hence of weight and space than others.
- (g) No conclusion as to the feasibility of liquid-oxygen systems for ship-based aircraft can be drawn since no liquid oxygen producing equipment suitable for shipboard use has ever been made.
- (h) The necessity for adding carbon dioxide to the high-altitude oxygen supply should be determined.
- (i) Present oxygen masks are wasteful of oxygen and can be improved.
- (j) The balloon system of carrying oxygen on planes is feasible for certain uses.
- (k) Solid chemical oxygen sources have many advantages for Naval use.
- (l) Solid chemical oxygen sources permit the development of hermetically-sealed chemical warfare resistant high-altitude flying suits.
- (m) Soda-lime is unsuitable for carbon dioxide removal in high-altitude oxygen apparatus.
- (n) Whatever oxygen source is used on a plane, an emergency source should also be carried.
- (o) Air super-charger systems (airtight cockpit or diver's suit) have the advantage of maintaining the personnel in the air environment to which they are accustomed, thereby introducing no new physiological problems.

Recommendations

65. It is recommended that:

Physiological Factors

- (a) A program of cooperative research be initiated to ascertain the physiological factors of high-altitude flight (cooperative with U.S. Army, Department of Commerce, etc.).
- (b) The need for using carbon dioxide in high-altitude oxygen be determined. (This is being studied by the U.S. Army Air Corps.)
- (c) The desirability of constructing a low-pressure, low-temperature "altitude chamber" for research on personnel and research, development, and test of equipment be considered.
- (d) The dangers from "bends" under high rates of climb be ascertained. (This is being studied by the Army Air Corps.)

Oxygen Sources on Planes

- (a) The development of re-breathing systems be undertaken.
- (b) The development of solid-chemical oxygen sources be expedited. (Bureau of Aeronautics project with Mine Safety Appliance Company.)
- (c) The use of the confidential C&R submarine air purification material for carbon dioxide absorption in high-altitude systems be studied.
- (d) The development of water absorbents for re-breathing systems be started.
- (e) The development of solid-chemical oxygen re-breathing systems suitable for use in chemical-warfare-proof flying suits be initiated.
- (f) The development of compressed-oxygen systems be continued with the object of increasing their reliability and economy and decreasing their weight.
- (g) Means for heating the oxygen supply to masks be developed.
- (h) The development of oxygen masks which are more economical of oxygen be attempted.
- (i) If the need for flight above 40,000 feet seems imminent, the development of pressure-tight cockpit planes and of "diver's suits" be undertaken.
- (j) The feasibility of "diver's suits" as a combination chemical-warfare-defense and supercharged-suit for use above 40,000 feet be appraised.

- (k) The desirability of obtaining the latest available foreign high-altitude equipment for inspection and test be considered.
- (l) The oxygen consumption of patrol planes be determined in flights in which the air in the cabin is enriched with oxygen (paralleling experiments by the Douglas Company.).
- (m) Following (l), the feasibility of using liquid oxygen to enrich the air in cabins of large multi-passenger shore-based planes be appraised.
- (n) The development of the balloon storage system for planes be undertaken primarily to determine its limitations and for possible use in training personnel.
- (o) The development of hydrogen peroxide oxygen generators for patrol planes be undertaken.

Oxygen Supply on the Carrier

- (a) The desirability of developing and constructing liquid oxygen rectification equipment suitable for shipboard use be determined.
- (b) The availability of commercial liquid oxygen at all Naval bases be determined.

66. The following recommendations made by Mr. J.E. Sullivan in reference (b) are quoted for comparison with the above:

"11. In view of the need for the development of more efficient means for supplying Naval Aviators with oxygen at high altitudes, it is recommended that the following program be carried out:

- (a) Continue refinement of present system, i.e., perfection of regulators and complete development of a combination face mask and a microphone. The regulators now on order appear to be an improvement over former types.
- (b) Design, manufacture and test at high altitudes an airplane with a pressure-tight cockpit. This is the major and important problem and direct attack on same is considered the most economical and expeditious manner of bringing the matter to successful conclusion. It is recommended that the cockpit be designed to withstand an internal pressure of one atmosphere for it should be able to withstand a working pressure of one half an atmosphere. It may be desirable to consider, in connection with that development, the R-1535 now being fitted with a two-stage, two-speed supercharger.
- (c) Cooperate with the Mine Safety Appliance Company in the development of the new chemical and in the perfection of means of utilizing and handling it.

- (d) Initiate development of an externally-driven supercharger for the cockpit of (b).
- (e) Conduct a thorough study of the work done and contemplated in the development of engine exhaust-driven superchargers with a view toward initiating development of an exhaust-driven supercharger for the cockpit.
- (f) Continue development of a self-contained oxygen re-breathing unit, utilizing the chemical mentioned above.
- (g) Investigate through actual flight tests the need for using a mixture of CO₂ and oxygen in lieu of pure oxygen in the present oxygen breathing apparatus.
- (h) Determine through flight tests, the conditions under which it is necessary to begin applying pressure to the body to provide for satisfactory absorption of the oxygen by the blood."

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This is a comprehensive discussion of the physiological aspects of altitude flying and include a bibliography giving 289 references to earlier work. A free translation of the summary of this article given by the author follows:

Summary

- (1) The breathing processes of the organism in rarefied air change not only the mechanism of breathing but also the chemistry of the body processes.
- (2) The increase in energy exchange results in an increase in body temperature and heat dissipation.
- (3) Oxygen deficiency changes the character of various organs, especially the heart.
- (4) Oxygen deficiency first affects the central nervous system. The resultant injury is first evidenced by modification and loss of intellectual functioning and derangement of muscular coordination.
- (5) The height attainable without breathing oxygen varies with different individuals; it is affected by activity, by diet, by toxic substances, and especially by certain construction features of the airplane, for example, the seat and the safety belt.
- (6) Breathing apparatus must be automatically governed by the lungs and must have provision for heating and moistening the inspired air; decision as to whether by adding carbon dioxide the height attainable can be increased without impairing health from prolonged use requires further research.
- (7) In view of the change in blood chemistry in rarefied air, research on the circulation of the blood at low pressure is essential.
- (8) The magnitude of the basal metabolic processes on the ground do not correspond to those at high altitudes.
 - (a) For computing the oxygen required at

high altitudes, the sea level values can only be used as a starting point.

- (b) In calculating the oxygen requirements the existence of an oxygen deficiency must be allowed for.
- (9) Nothing is known as to the effects of cosmic rays and of cold on the breathing processes.
- (10) The relation of the dissolving power of the red blood corpuscles or of the ability of the blood corpuscles to take up oxygen to diminution in air pressure is not clearly known.
- (11) Further, nothing is known as to the water endurance of the body and the changes in the resynthesis of lactose into glycogen or of the consumption of albumin in place of glycogen at low pressures.
- (12) Acceleration affects can be of significance in breathing, and indeed these affects vary greatly with altitude. Also acceleration affects must be considered in mounting the apparatus.
- (13) The limit to the use of oxygen breathing apparatus is about 14 kilometers (about 46,000 feet).
- (14) Also, even breathing ample oxygen, exceeding this altitude limit results in mental and physical derangement which can persist for several hours.
- (15) The injury to the organism from prolonged breathing of oxygen sets a limit to the amount of duty a high altitude flier can be called upon to perform. The fatigue resulting from remaining at high altitudes limits the amount of time which flying personnel should be called upon for duty.
- (16) The significance of the state of fatigue of the organism for the breathing process makes it imperative that the attention required to fly the plane and the arrangement of its components be such that the pilot's activity can be reduced to a minimum with safety. The greatest possible convenience and comfort are not luxuries in airplanes, but instead are urgent necessities in order to conserve breathing and therefore be conserving of efficiency.
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TABLE 1

Physical Properties of Oxygen

Molecular weight: 32.00.

Critical constants: $T_c = -118.8^\circ\text{C}.$

$P_c = 49.7$ atmospheres.

Density: Gas at standard conditions = 1.43 grams per liter.

= 0.089 pounds per cubic foot.

: Liquid at boiling point = 1.14 grams per c.c.

Boiling point = $-183^\circ\text{C}.$

Latent heat of vaporization = 51 calories per gram.

Vapor pressure = $-210^\circ\text{C}.$ 10 mm mercury = 0.39 in mercury.

-203	50	1.97
-198	100	3.94
-194	200	7.87
-191	300	11.8
-188	400	15.7
-187	500	19.7
-185	600	23.6
-184	700	27.6
-183	760	29.9

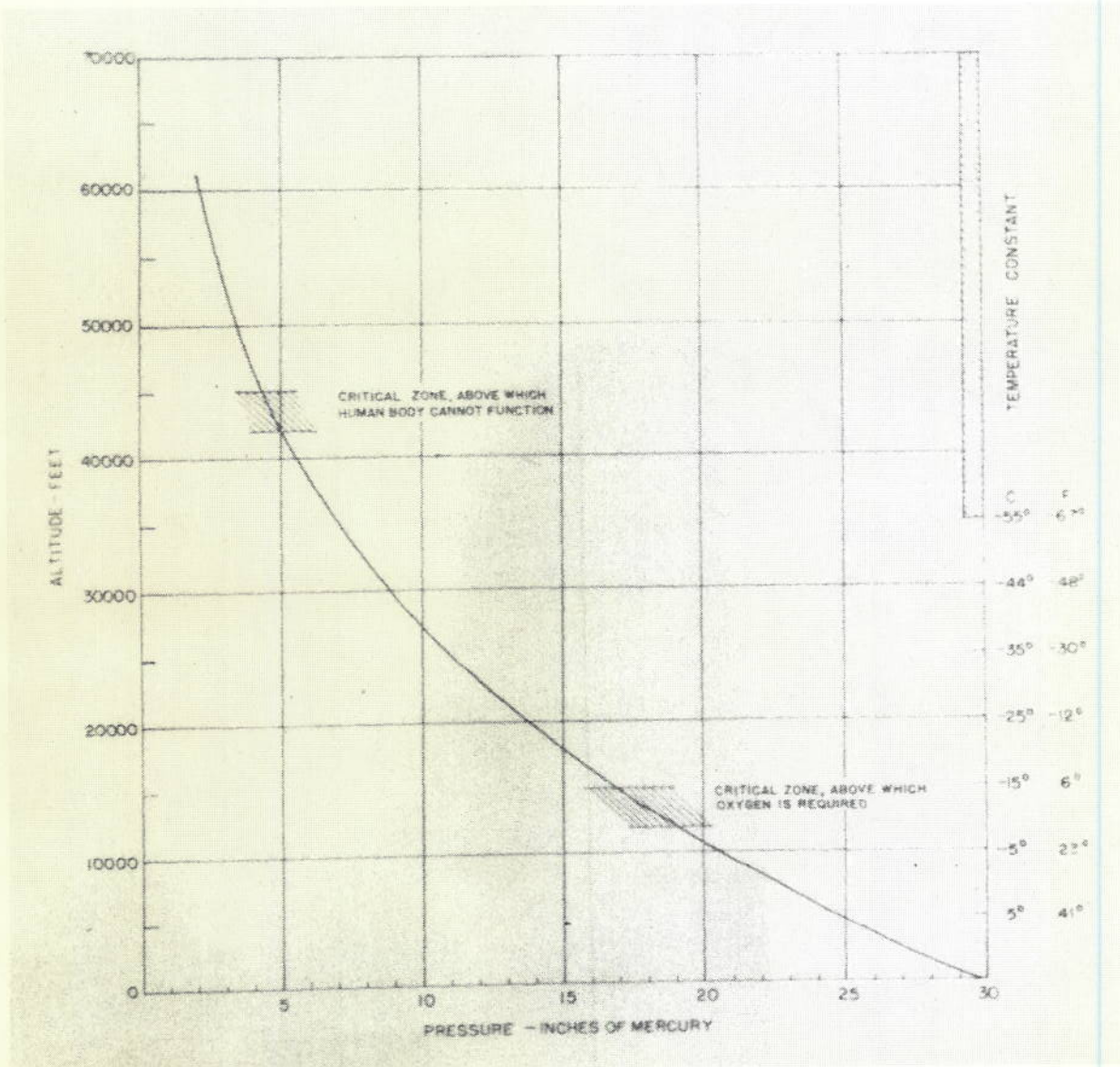


Plate 1

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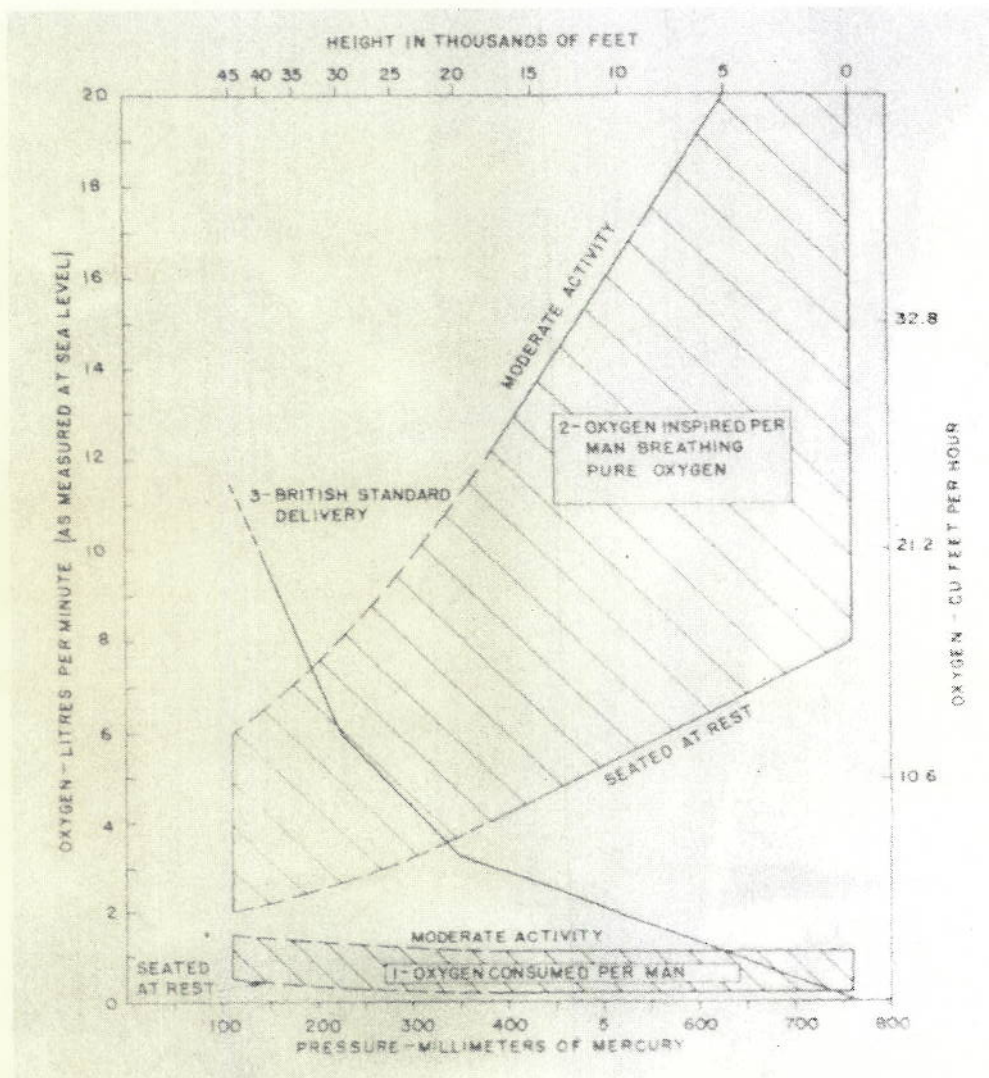
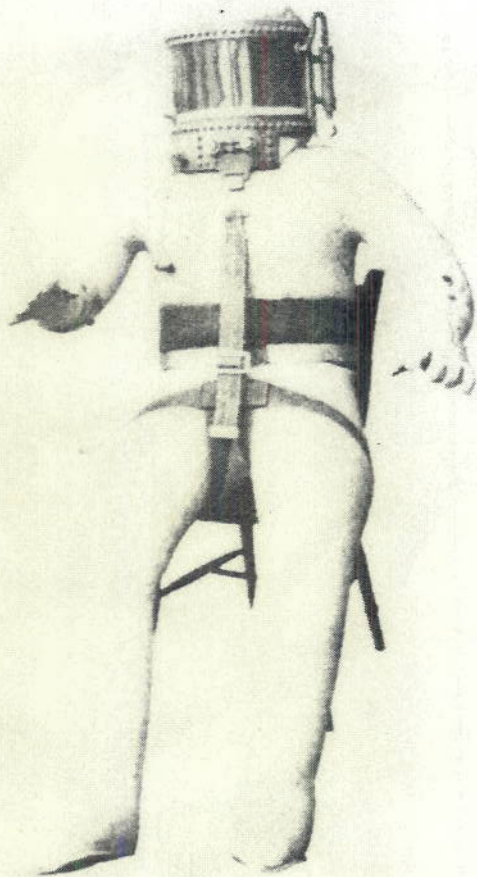


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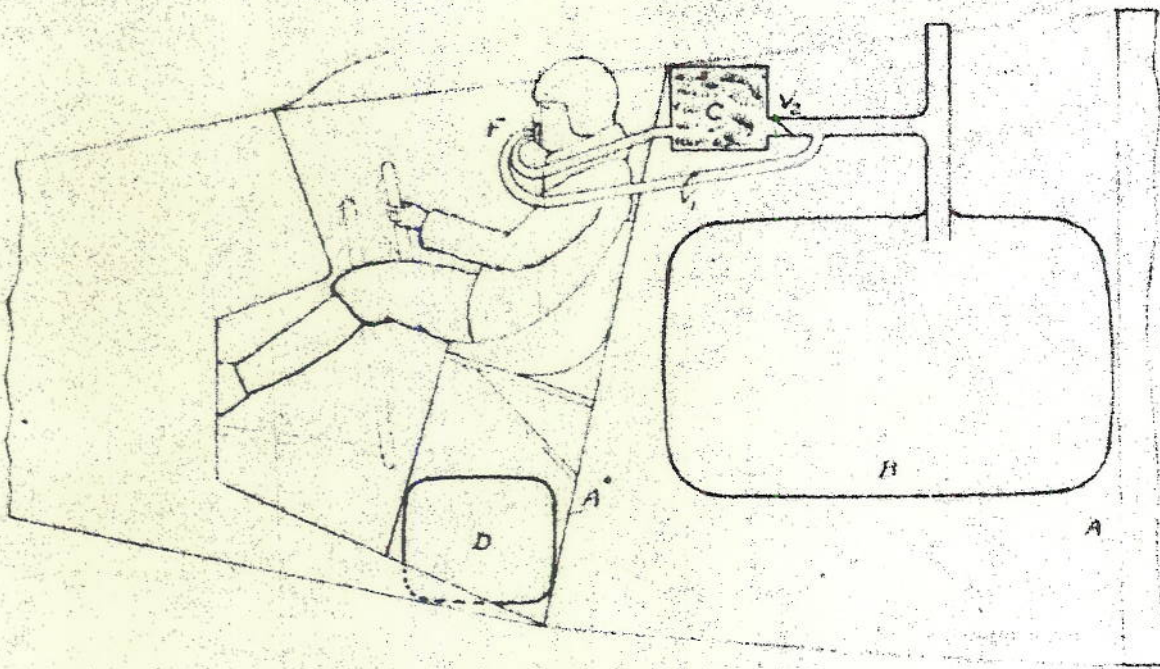
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PLATE 3



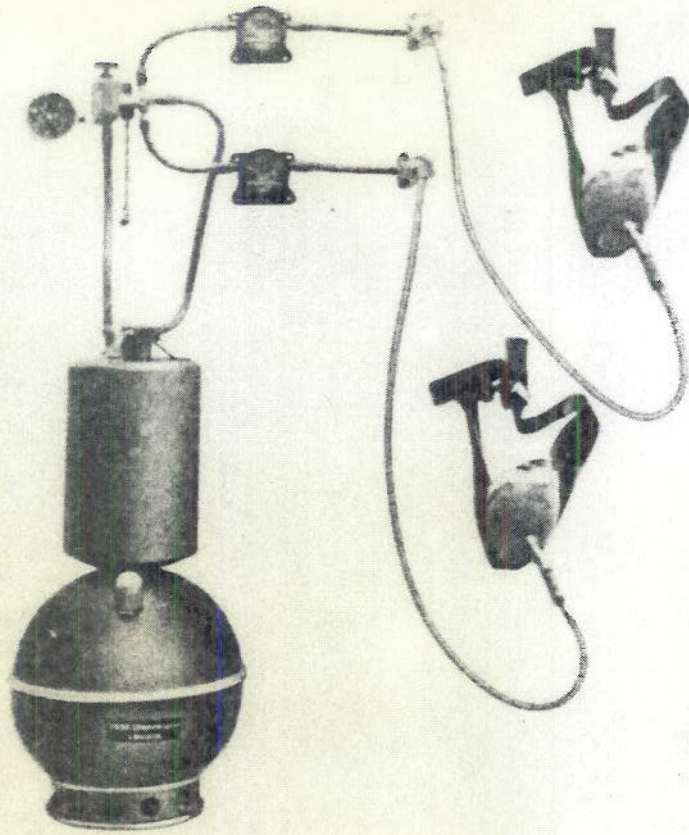


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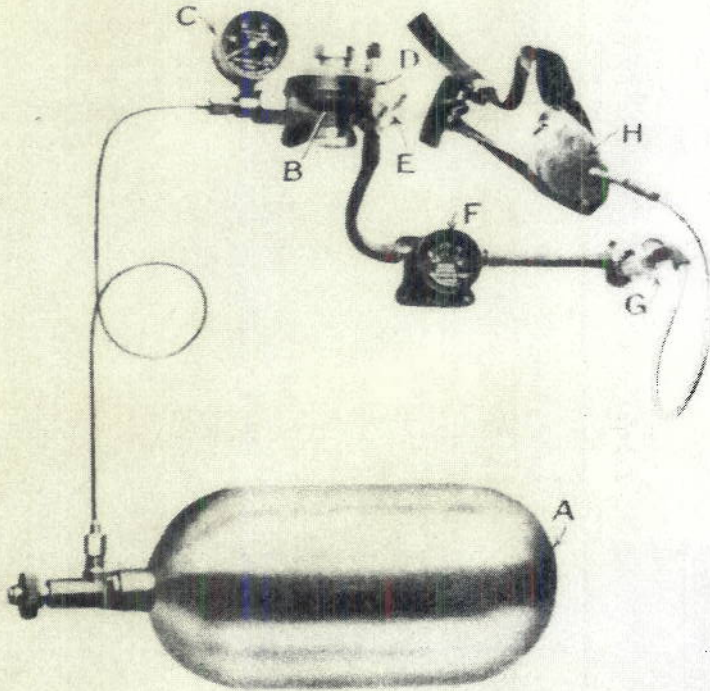
Plate 4



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PLATE 5

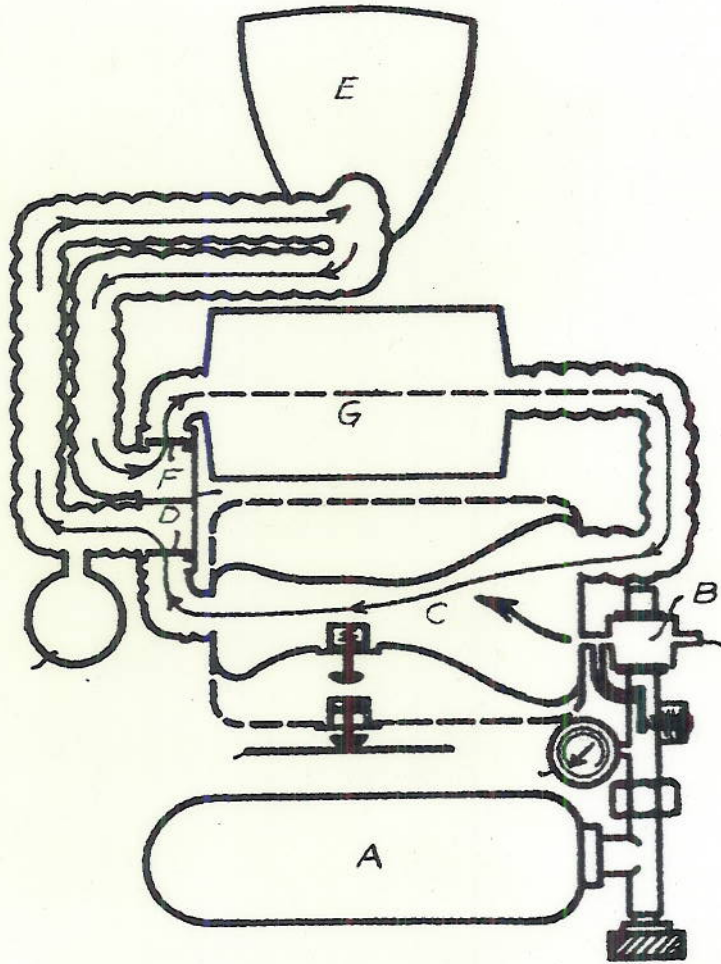


PLATE 7

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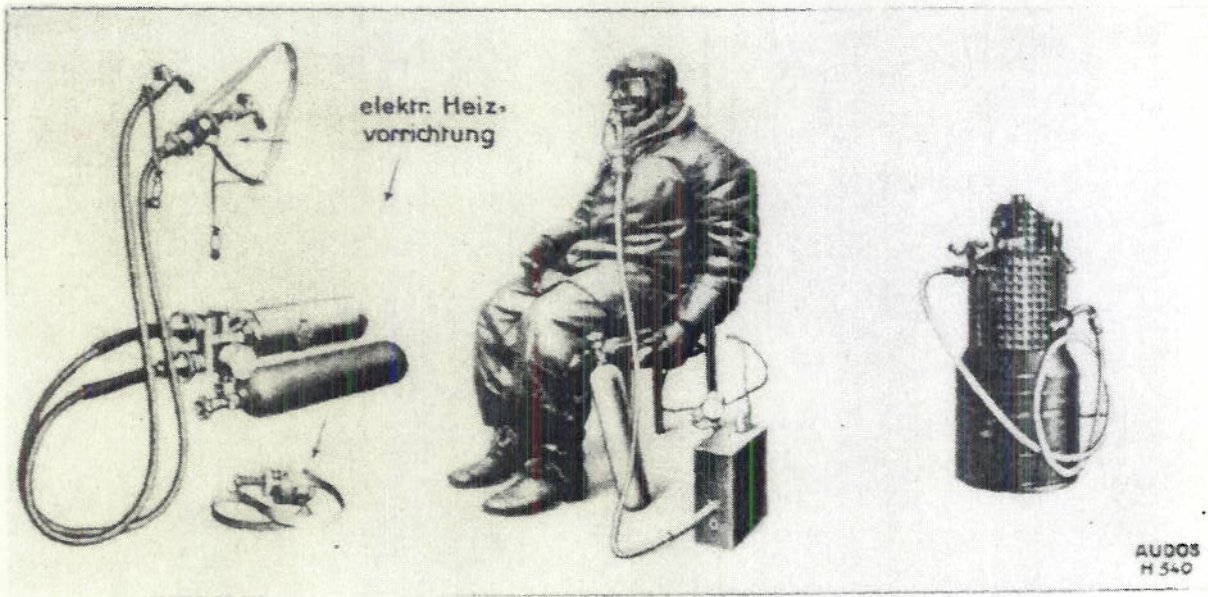


PLATE 8

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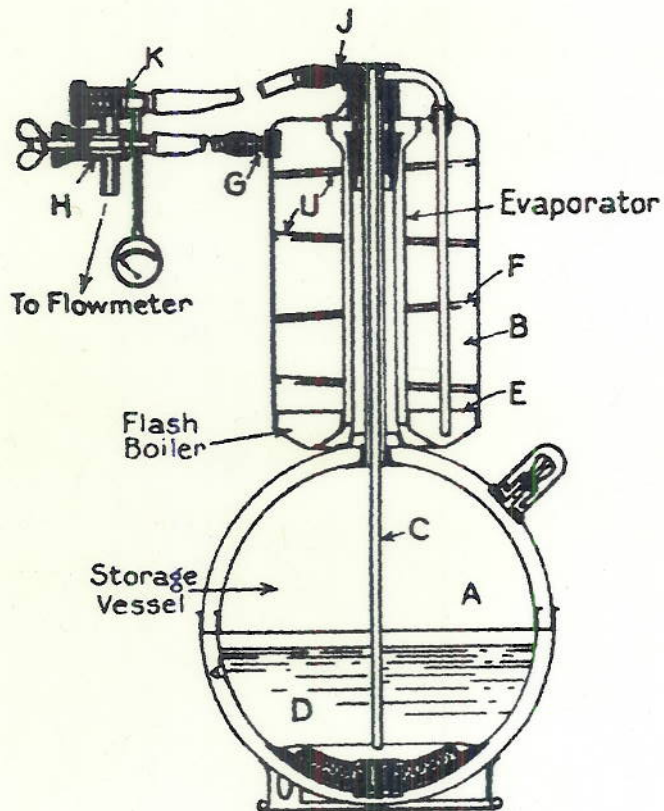


PLATE 9

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