Oxygen Safety—Submarine to Aircraft

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The following material exploits the possibilities of finding new approaches employing simpler, highly standardized, emergency oxygen supply systems for the broad range of new aircraft in development and on the drawing boards. The ideal standardized system will meet the requirements whether they are for 4 or 400 passengers. This paper does not take a hard position on which oxygen system should be used for a specific aircraft type, but challenges the designer to preassess the possible advantages, particularly safety, of solid oxygen generators over other types of supplies, in view of the progress and success attained by the Navy in the development of submarine equipment. The prime objective is to promote simplicity, reliability, and maintenance characteristics which contribute to over-all vehicle safety by the reduction of fire hazards and ground crew servicing. The discussion points to areas which may yield measurable improvements and is not fault finding with operating systems, which are demonstrating good performance and a high degree of safety.

Oxygen Systems Safety Evaluation

THE increasing performance capabilities of new aircraft and the broad range in the number of crew and passengers involved make necessary a constant evaluation of life support systems technology. The systems under consideration are those of the emergency oxygen supply. Granting that all of the Federal Air Regulations can be met for the commercial aircraft, and that all certification and military specifications can be met for military aircraft, there remains a basic safety problem in the oxygen supply source. The design of the supply must be continuously evaluated by the designer if improvement is to keep pace with the advanced vehicle design.

In terms of emergency oxygen supply safety, three basic areas are of concern and must be considered at the system design selection level: 1) meeting the physiological requirements of the passengers and/or crew, 2) minimum mechanical operational complexity and/or fire hazard to the aircraft, crew and passengers, and 3) simplicity in ground service requirements. These operational and safety areas are not new and, in general, are being met in all relative aspects.

Oxygen Safety—Submarine to Aircraft

The submarine element provided the source of information from which to draw scientifically acceptable data relative to the three basic safety areas. The solutions obtained for the special problems of supplying the breathing atmosphere for submarine crews provide a large measure of support to the currently used oxygen systems and the basis for adding the solid-state generators to the list of candidate aircraft emergency oxygen supply systems. Early writings[1] on air purification were concerned basically with the physiological aspects of the submarine breathing atmosphere purification and sought solutions which would provide a safe, nonexplosive, toxic-contaminant-free atmosphere for the crews. The basic problem of the submarine equipment designer is to provide safe, economical, and relatively compact generating and circulating systems with a minimum of sophistication and logistics. A typical integrated system for nuclear submarines in which the location of major air purification equipment is shown in Fig. 1, each portion of which is independently controlled.

In some of the earlier nuclear systems, prior to the electrostatic precipitator, the chlorate candle system was used more frequently than in current systems. The chlorate candle is in full use by the non-nuclear conventional submarine. Obviously, some of the submarine equipment such as the CO_2 scrubbers, H_2/CO burners, carbon filters, atmosphere analyzer, and the large oxygen flasks are not required for the aircraft emergency oxygen supply.

Resulting from early work of scientists such as Lamb, Bray, and Frazer[2] in the development of the catalyst Hopcalite, which has the ability to catalyze the oxidation of carbon monoxide to carbon dioxide at room temperature; Brown[3] and Carpenter,[4] as well as Du Bois,[5] on submarine habitability; and the post World War II efforts of Miller and Piatt[6] and their associates, of the Navy Research Laboratories, we have valid scientific data and background to justify reconsideration of the solid-state (chlorate candle) emergency oxygen system. The excellent work of scientists from other countries and from the U.S. companies, such as M. H. Treadwell, Electro Chemical Div. Du Pont Co., Oldbury Chemical Co., Mine Safety Appliance Co., Scott Aviation Corp., and U.S. Divers Corp., adds credence to the progress in developing a solid-state oxygen generating system with the desired safe and toxic-contaminant-free characteristics. These firms and their scientists deserve recognition for their many years of persistent supporting effort.

Types of Oxygen Systems

Six basic types of aircraft oxygen systems may be evaluated for selection. These are: low-pressure gaseous, high-pressure gaseous, low-pressure liquid, alkali super oxides, chlorate candles, and electrochemical generators. The tradeoff parameters that must be considered in the selection of an oxygen system are discussed later. Table 1 identifies many of the unique advantages and disadvantages of the six basic systems.

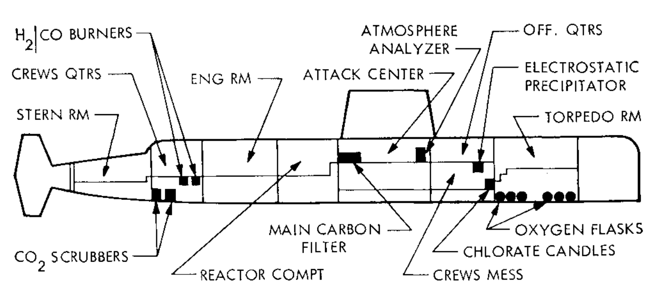

Fig. 1 Atmospheric purification equipment in a typical nuclear submarine.

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Low-Pressure Gaseous Oxygen Systems

These systems (400 psi) are similar to high-pressure systems in that the cylinders are manifolded through check valves to prevent depletion of the entire supply should a leak occur at one cylinder or in its plumbing. Since no high pressures are encountered, low-pressure tubing with flared or flareless connections are satisfactory. Large storage bottles are also required.

High-Pressure Gaseous Oxygen Systems

These systems are supplied by one or more 1800–2000 psi cylinders of aviator's gaseous breathing oxygen. These cylinders are connected in parallel to high-pressure distribution lines that lead directly to breathing regulators, to which the breathing hoses and masks are attached. The fire resistant and strength qualities of stainless steel make it particularly desirable for plumbing in the high-pressure system. These cylinders are also manifolded by check valves, tees, and crosses upstream of the distribution lines, much the same as for the low-pressure system. In many instances, an external filler valve and connecting plumbing are included to facilitate the replenishment without removal of the cylinders from the aircraft. Regardless of the type of breathing regulator used, the regulator must reduce the supply pressure to breathing pressures (generally less than 0.1 psi). Reduced-pressure gaseous oxygen systems consist of a high-pressure section essentially as described previously, which is connected through a pressure reducer to low-pressure distribution lines leading to the breathing regulators. Lengths of high-pressure lines are kept to a minimum in this arrangement. In some installations, the reducer is incorporated as a part of the cylinder connection, thereby eliminating the need for interconnecting high-pressure plumbing. Because of the high supply pressures in the high-pressure-type systems, they are susceptible to sudden high-pressure surges when the contents of charged oxygen cylinders are introduced into the system. Such surges can produce dangerously high temperatures due to compression of the gas at confined downstream locations such as at reducers, check valves, regulators, etc. As a consequence, extreme care must be exercised in the selection of materials used in valve seats and gaskets, particularly with regard to components of check valves and pressure reducers. When it is necessary to use elastomers in lieu of metals for fabrication of parts to effect proper operation and sealing, materials that have successfully passed "bomb-oxidation" tests must be specified. Use of slow opening-cylinder valves requiring 5 to 6 full turns to open has proven an effective means of reducing pressure surges so that hazards are reduced.

Liquid Oxygen Systems

These systems utilize a converter to provide storage and pressurization of liquid oxygen. Low-pressure converters store oxygen at a nominal pressure of 70 psig; high-pressure converters (normally used only for emergency bottle recharging) store liquid oxygen at 300 psig. A typical 70-psi converter consists of a liquid oxygen container (Dewar type), pressure opening and pressure closing valves, check valves, relief valve, and gaseous generating coils plus the many other connectors, gages, etc. Liquid oxygen installations are subject to the design precautions for oxygen systems in general, but some properties peculiar to liquid oxygen presents the designer with problems requiring extra care, such as overboard dumps, no liquid traps, etc. For example, one problem involves the volume ratio of liquid oxygen at basic cryogenic temperature to the volume of gas produced from a unit quantity of liquid (about 862:1). If revision to gaseous state occurs too rapidly, a hazard results.

Alkali Metal Peroxides and Superoxides

These materials have been of interest for many years as purification media because of their "double-barreled" effect: oxygen may be released for breathing,[7] and the alkali residue may be used to absorb the carbon dioxide produced in the breathing cycle. This possibility is most desirable when they can be controlled. For the aircraft emergency oxygen supply a number of problems still must be solved, particularly those of sealing from moisture, starting flows, surveillance, etc. The Navy continues to pursue the use of alkali superoxides for "Atmospheric Regeneration Aboard Submarines."[8] The problems of installation and the dangers of stowed oxidizers are of serious concern in the submarine installation and likewise would be of serious concern in aircraft applications. The oxidizers are more difficult to control, since water releases the oxygen, and with large quantities of hydrocarbons present, the mixture, plus a gradually increasing oxygen atmospheric content becomes a powerful explosive. In the breathing canister, during the breathing cycle, each molecule of oxygen combines with 0.83 molecules of carbon dioxide to produce an oxygen-rich atmosphere (an O_2/CO_2 ratio about 1.2:1). This alone is not a hazard, providing the atmosphere does not become too enriched. Miller found in his experiments that potassium oxide gave superior results for breathing apparatus.[7]

Chlorate Candle Oxygen

The mechanism utilized in chlorate candles is the decomposition of sodium chlorate at relatively high temperatures (700°–800°F) into sodium chloride and oxygen. The heat for the decomposition is supplied by the oxidation of iron powder mixed with the chlorate. In order to keep the process from consuming a great quantity of the oxygen, the quantity of iron is kept to a minimum. There is a tendency toward the liberation of small amounts of chlorine. Barium peroxide, or barium dioxide, may be added to provide an alkaline medium for removing the trace amounts of chlorine that may be present. Early in the development of the chlorate-candle oxygen system, the gas had to be filtered to remove a small amount of alkali chloride smoke. This problem has been overcome and the oxygen mixture may be breathed directly without an external filter.

Electrochemical Oxygen

With the development of the nuclear-powered submarine came the shift from battery power to nuclear-generated electrical power for underwater propulsion. This development reduced the high premium for electric energy which made it possible to consider electrolytic oxygen generators. The basic principle of the electrolytic generator is the application of a current across nickel-cadmium plates, immersed in an appropriate container filled with water. The voltage impressed across the plates initiates the hydrolysis action separating the H_2O molecule, releasing hydrogen and oxygen.

The first type of generators, in general, used diaphragms to separate the oxygen from the accompanying hydrogen. This type of generator has been in commercial use for some years. The early submarine generator developed had to solve many new problems. One solution was the development of the high-pressure cell, which could meet the selected 3000-psi operating pressure. During the early development, one unit operated at 200°F at an anodic current density of 1.5 amp/in.^{2} at 30 v. One prototype, for example, could produce from 8 cells enough oxygen from 24 gal of water/day to support 75 men. The power requirement for enough oxygen for these cells was about 750 amp each at 3 v, 18 kw (24 hp).

New developments in the nickel-cadmium "split-cells" have shown appreciable improvement in performance over the H_2-O_2 cells by weight reduction, lower-power consumption, less-heat rejection, etc. The nickel-cadmium "split-cell"

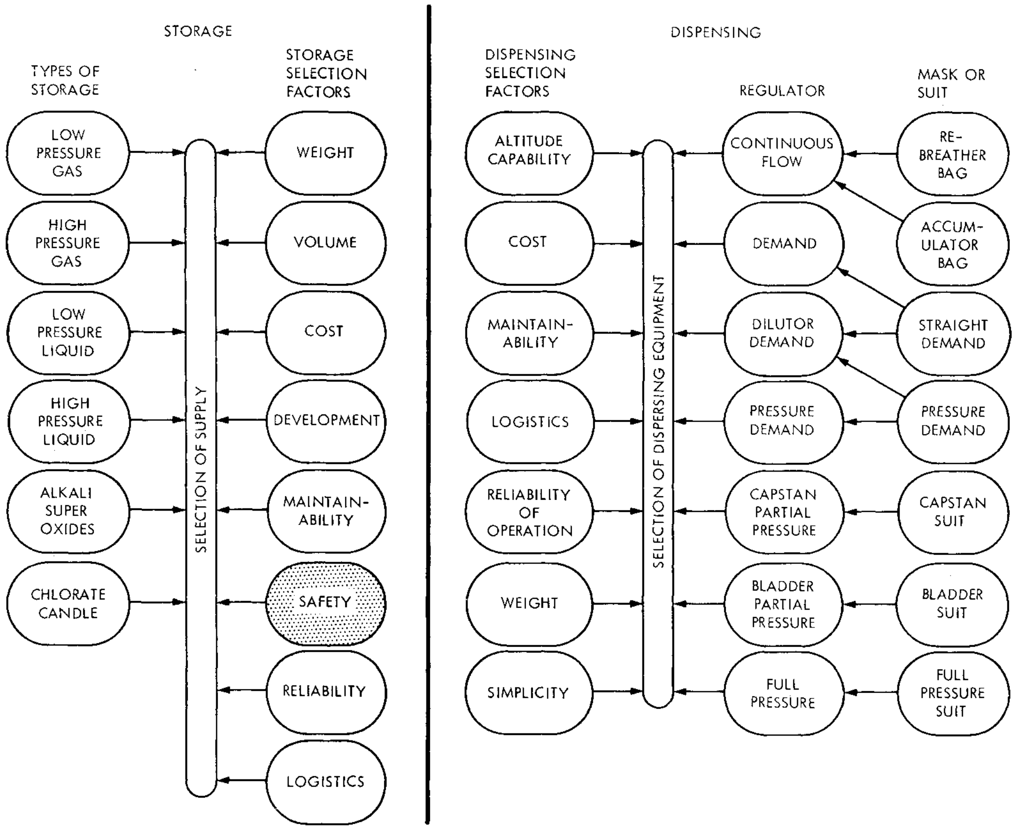

Fig. 2 Types of oxygen systems.

for oxygen production appears to be the most attractive continuous source. For the emergency application, the system requires further exploration. For some time, research has been underway to develop a suitable unit for aircraft and sufficient progress has been made to warrant continuing effort.

The preceding paragraphs provide only a minimum description of the six candidate systems. However, Fig. 2 provides a check-list diagram of those factors that influence safety, principally from the viewpoint of storage and dispensing. Some 35 factors must be carefully weighed and used to govern the design of a safe emergency oxygen supply.

Installation Factors

Among the tradeoffs which require early consideration in the development of a satisfactory design are those parameters diagrammed in Fig. 2, and the unique advantages and disadvantages from Table 1. Two items in particular rank high on the list following safety. They are storage-container weight and container volume. Storage-container weights are proportionately scaled in Fig. 3 for five of the six basic candidate systems discussed earlier. The high-pressure liquid oxygen supply system is not shown.

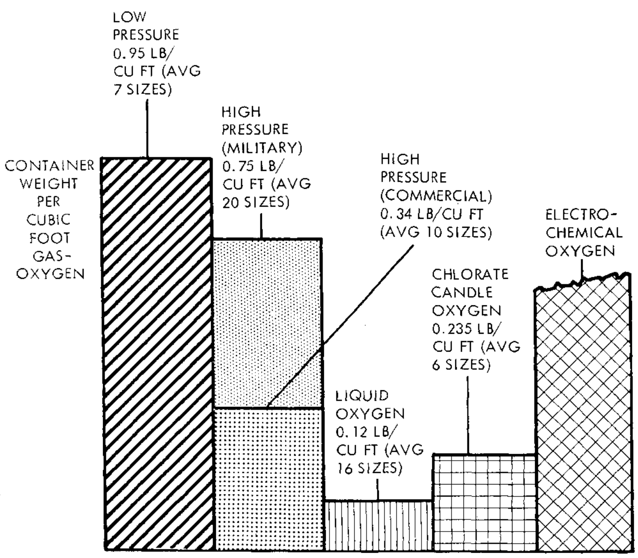

Fig. 3 Type-storage-weights.

System evaluation requires a very careful examination of the servicing and operating personnel's characteristics, education, skill level, performance when using precise procedures, rigid self-discipline, and ability to accept responsibility. Unless the servicing and using personnel are adherent to the handling techniques, a high fire and personnel risk develops. Figure 4 is a proportional plot of the storage-container volumes for the five systems illustrated in Fig. 3. The plots in Figs. 3 and 4 are based upon the number of samples indicated for each. In general, the values are relatively realistic of the current state-of-the-art.

Installation Evaluation

Normal Operation

As has already been discussed, the primary requirement for the aircraft is the provisioning of sufficient oxygen concentration at high altitudes to sustain safe and adequate human performance, without fear of physiological damage. Under most normal operating conditions, the level of oxygen concentration is provided by the aircraft's cabin/cockpit pressurization systems which provide a higher oxygen partial pressure than minimum physiological requirements. However, these higher pressurization capabilities afford a greater margin of physiological safety, reduce the general discomfort of rapid descent, and to some extent (particularly in the transport aircraft) provide more time for emergency equipment dispensing and donning. Even so, the emergency supply equipment is designed to be dispensed and donned safely at the pressure-altitude limits specified.

Table 1 Some of the unique advantages and disadvantages of oxygen systems

Oxygen-storage system	Advantages	Disadvantages
Gaseous low pressure	Reduced fragmentation Reduced leakage Reduced fire hazard No handling temperature problem	Heavy—large volume Requires in-plane refill Requires handling equipment and service area Pressure regulation required
Gaseous high pressure	Less volume than low pressure Lighter than low pressure No handling temperature problem	More pressure regulation required Highest fragmentation hazard Highest leak rates Higher spontaneous fire hazard Requires sophisticated ground handling equipment
Liquid	Less volume than high pressure Lighter than high pressure Less pressure hazard (normally) Little pressure regulation required	Requires special maintenance and service facilities (clean room) Requires protective garments for personnel Requires sophisticated ground handling equipment No traps in system Cold handling temperature Properly located overboard discharge Liquid drop/run problems Heat leakage High contamination problem, fire—toxic
Super oxide	No pressure regulation required Requires minimum service crew Requires minimum ground facilities No unit size limitation Low contributor to fire Smallest volume Lowest weight Bacterial depressant No static pressure problem Indefinite storage if hermetically sealed No pressure regulation required Nontoxic	Material contact problem Tissue destroyer Fire if hydrocarbon or organic Requires pumping, air Relatively slow starting Requires filtering (dust) Exothermic (moderate) lower than chlorate
Chlorate candle	Requires minimum service crew Requires minimum ground facilities Small volume Light weight Simplicity of operation No distribution system Indefinite storage life Nontoxic No pressure problem Easy, quick start Can withstand gunfire fragmentation Low fire contributor Normal size limitation High installation flexibility No pressure regulation required	Programmed flow schedule (simplest system) Moderate exothermal insulation required Must be kept free of hydrocarbon Inadvertant operation exhausts supply
Electrochemical	Minimum ground servicing Unlimited oxygen supply (from environment) Relatively free of contamination	High-power requirement Large size—heavy Critical fluid to power ratio (during emergency) By-product hazardous (requires dumping or burning hydrogen) Requires demineralized and particulate free water Requires particulate free air Maintenance characteristics not established Must be kept hydrocarbon free Some explosive hazard Heat-sink requirement

Evaluation Order

The order of importance in the evaluation of safety factors remains as identified earlier, i.e., physiological, mechanical/fire hazard, and ground servicing.

Sufficiency of Supplies

The designer must ascertain that there are sufficient oxygen supplies aboard, and that all Federal Aviation Regulations (FAR) requirements and/or military specifications are met. Physiological safety must be rechecked and a final evaluation conducted against possible emergency situations which could occur for the specific aircraft type. The designer evaluation must verify the sufficiency of supplies for crew (supplemental oxygen) plus emergency provisions (protective oxygen); passengers, plus 10% extra (supplemental oxygen); passenger emergency (first aid oxygen); flow rates and total quantities; accessibility and dispensing; storage; servicing, etc.

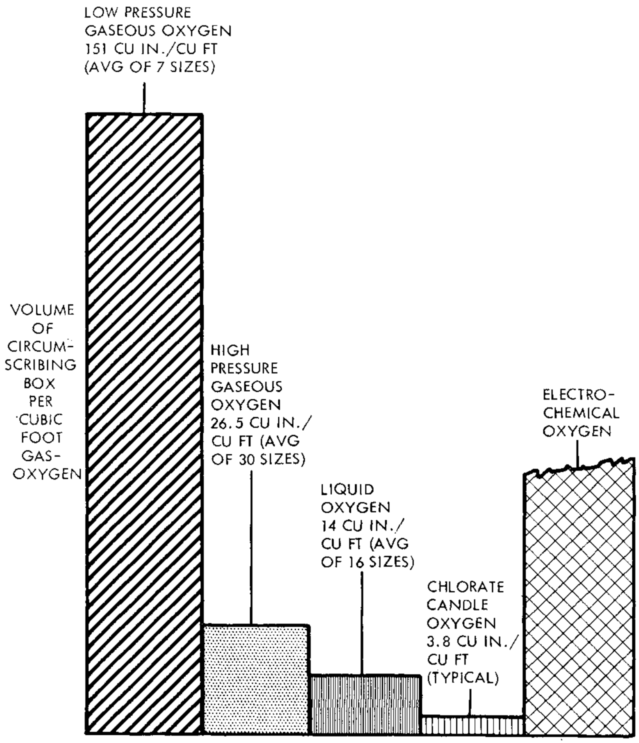

Fig. 4 Type-storage-volume.

Assumed Evaluation—Test Situations

The evaluation must also be made for various possible dynamic situations under which it would be necessary to require their use. Some of the possible situations most easily envisioned are 1) unanticipated decompression of the vehicle at any altitude within its normal flight operating envelope, 2) aborted takeoff or a short hard landing, wherein the vehicle could be damaged but passengers not seriously injured, or 3) ground servicing accident which could cause either explosion or fire.

Expansion of Situations

1) In the case of decompression, all elements of the system for the flight crew and/or passengers must function properly and reliably to minimize hazard.

2) In the case of the aborted takeoff, or short landing, the primary concern becomes that of safe escape through the dust and possible smoke. If there is fire, four additional problems develop: a) protection of passengers and flight crew from inhalation spasms caused by the smoke and dust, b) sufficient breathing air/oxygen to progress to the emergency exit, c) provision for a means by which passengers can see to find their way to the emergency exit, i.e., keep smoke and dust from the eyes, and d) the contribution of the emergency oxygen system if ruptured to sustaining and accelerating the fire.

3) Ground servicing accidents are not only expensive as the result of damage, but are complex, because the cause can be difficult to establish. In many cases it is necessary to determine if the cause was the fault of the personnel involved or a basic weakness in the design. The attitude might be taken that if the design was "right" the incident would not have occurred. This position is, of course, weak in the sense of blaming everything on the design. The manufacturer should in all known cases, when he has found such weakness, correct the deficiency. In most of the situations in which a difficulty is encountered after a system is in service, the designer was unable to foresee the difficulty or he would have corrected it. An example of such a problem follows in the paragraph on "Unforeseeable Oxygen Fire."

Certain problem areas are anticipated with common usage and among these are 1) the level of training and skill required of the ground crew, 2) personnel protective equipment, 3) simplicity or "fool-proofness" of servicing connections (contamination protection), 4) proper service carts, 5) location of supply recharge points (accessibility), 6) field supply, maintenance and repair facilities, 7) onboard flight crew status indicators, 8) degree of standardization of service equipment and the aircraft system, 9) regulations, procedures and practices, and 10) the frequency of use and type of equipment. Although the scope covered here does not cover all of the known areas of precaution, Fig. 5 illustrates the type of protective equipment required for the ground service personnel.

Unforeseeable Oxygen Fire

The damage shown in Figs. 6–8 was due to an oxygen system fire. The ship was on the ground at the time and was being prepared for flight. In the process of connecting recently refilled bottles to the passenger oxygen system, located in the aft baggage compartment, fire broke out in the immediate vicinity of the connection to the larger of the two bottles. The fire damage and subsequent extinguisher chemical action was extensive. The repair involved complete removal of a section of the fuselage and the floor and the

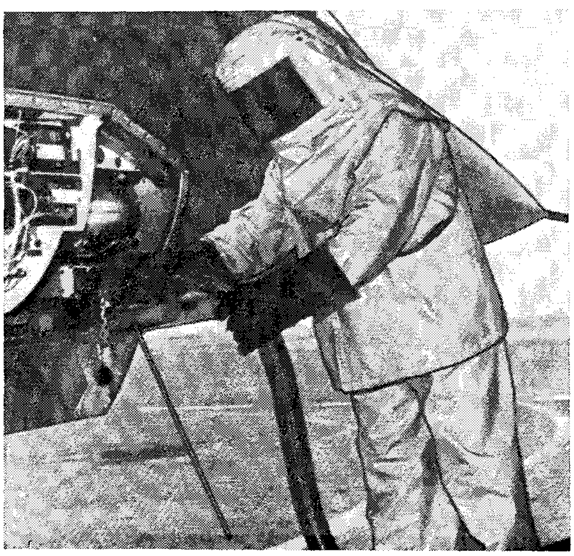

Fig. 5 Liquid-oxygen servicing garments.

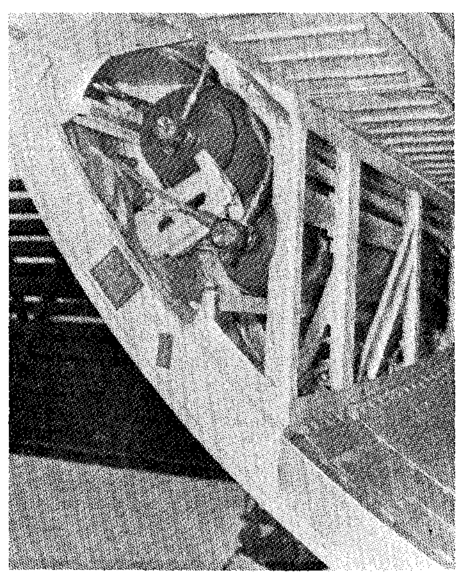

Fig. 6 Oxygen installation before fire.

Fig. 7 Oxygen fire damage.

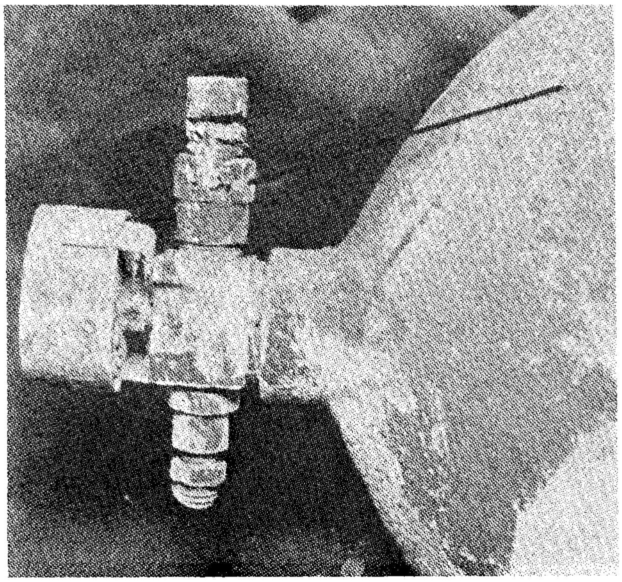

Fig. 8 Possible origin of fire.

installation of new systems within that area such as hydraulic, controls, oxygen, anti-ice and electrical.

The investigation of this accident revealed that the fire started adjacent to or inside the outlet fitting attached to the large oxygen bottle. However, the actual cause of ignition was not definitely established.

Resulting from the investigation, new procedures for installation and servicing the oxygen system were immediately formulated and distributed. Further, after extensive research, design changes were initiated to 1) install a slow opening hand valve in lieu of the automatic opening valve used, and 2) install two positive action check valves in lieu of the "T" double check valve. This corrective action was effective and no further oxygen fires in this installation have been experienced. The example used here, however, exemplifies the type of safety problem and experience encountered by aircraft designers and builders.

Total System Evaluation

A careful examination of the operating cycle, duration, quantity required per flight or usage, type of existing or servicing facilities/equipment available or required, and service personnel background, have a significant influence upon selection and design. In addition to the "type" effects upon procurement and operating cost is the extent of care taken by the design, safety, and human engineering systems integration groups, to assure that the conversion to a different type of supply system does not introduce new or hazardous situations, by unfamiliarity or conditioned operating procedures. A thorough and complete design analysis, with incorporated provisions to avoid this type of safety problem is paramount to choice of a successful system. This consideration should outweigh reasonable cost variations and installation tradeoffs. During the concept and design phases, applying a rigorous set of ground rules and appropriate value check lists, it is quite common to find that a combination of systems is most advantageous.

The commercial transport provides an example of the situation where the crew is supplied with one type of oxygen system and the passengers might be supplied with another. This is because of the frequency of use and extended safety requirements for the crew and the infrequency of use on the part of the passengers. Figures 9 and 10 diagram two versions of a Lockheed Electra oxygen supply system. The systems chosen and diagrammed in Fig. 9 provide high-

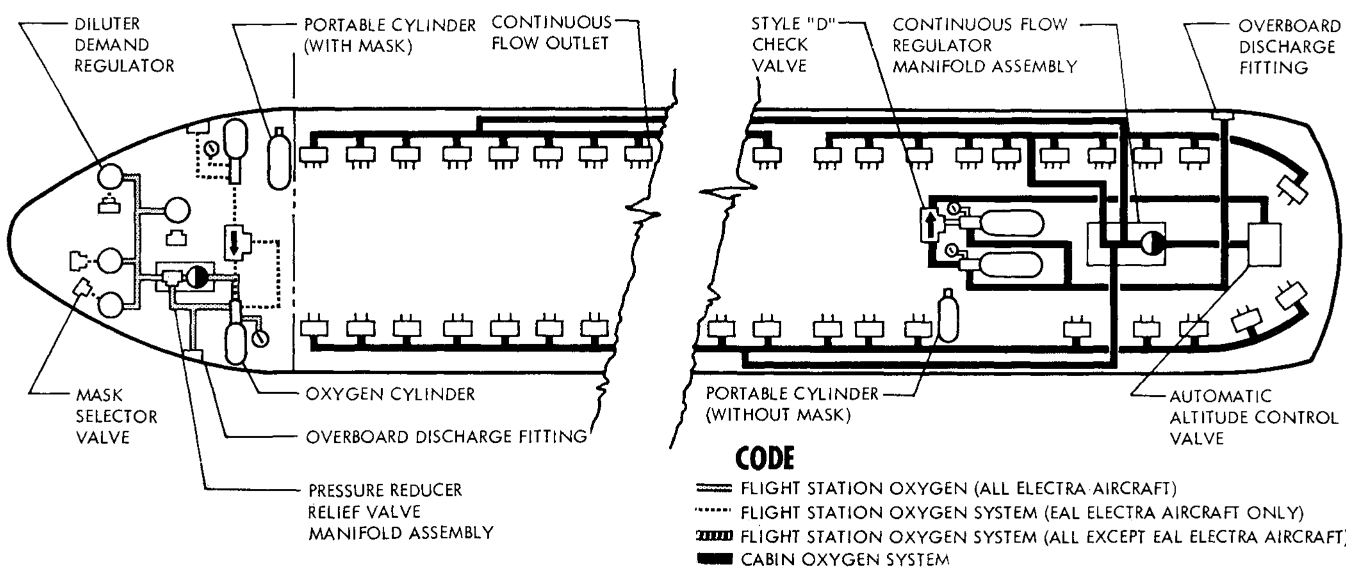

Fig. 9 Electra oxygen system diagram.

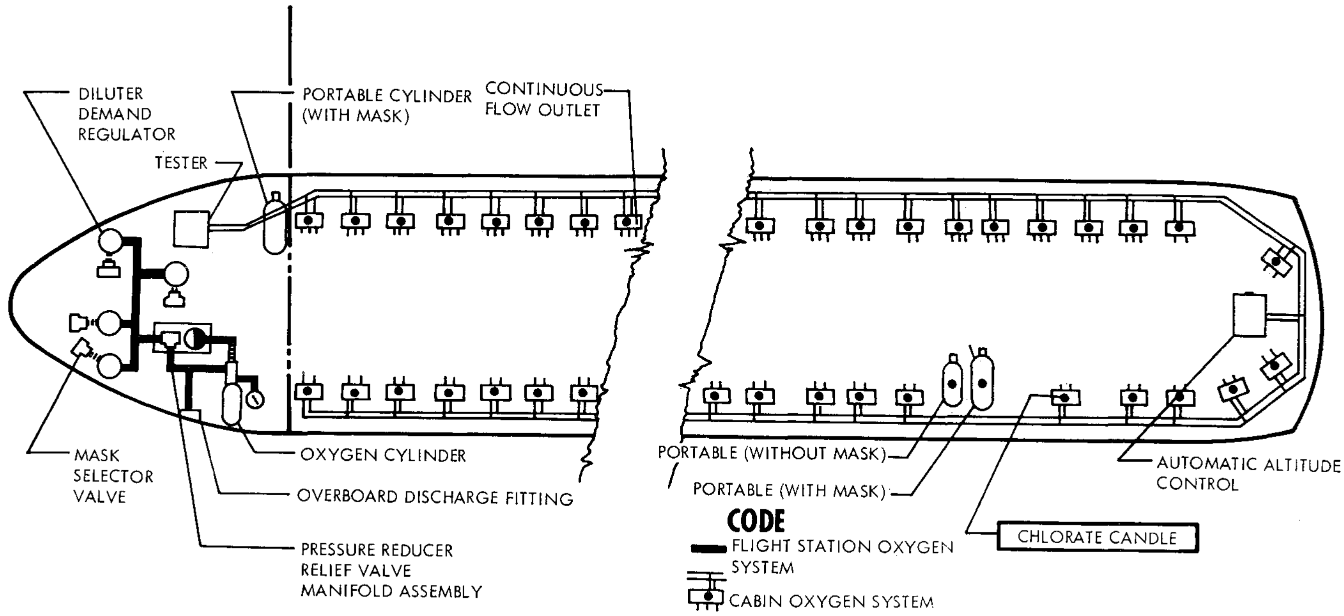

Fig. 10 Chlorate-candle oxygen system diagram.

pressure gaseous oxygen for both flight crew and passengers. This schematic also illustrates the variations or flexibility (flight crew station in this example) that may safely be used to meet the requirements of the using airline, concurrently meeting all FAR and safety requirements. Figure 10 illustrates provisioning the same aircraft with a high-pressure gaseous oxygen system for the flight crew and a solid-state (chlorate candle) system for the passengers and first-aid oxygen.

Assuming for purposes of simplification that the crew provisions are essentially of the same type, have equal cost, operational equivalence, and afford more than adequate safety, then the cabin system may be examined with relative freedom from further tradeoff analysis on system mix. From a cursory examination of the two diagrams, several interesting and promising factors may be identified which could contribute further to safety assurance. The points for early iteration tradeoffs between solid state and high pressure gaseous oxygen systems are as follows: 1) Elimination of all high-pressure storage containers. 2) High-pressure regulation and distribution control. 3) Elimination of the tubing runs; this is, of course, countered against initiation and operational check circuits. (The latter, if properly designed and installed, are less subject to degradation and normal structural flexing than is pressure-tube leak integrity.) 4) Simplification of individual distribution manifolds and drop-out mechanisms by the use of modular chlorate candle units. 5) Improved reliability, hence safety by design of initiation circuitry, so that an individual malfunction would not make other units inoperative (comparison here would be to ruptured lines, or high leakage in gaseous distribution systems). 6) Expectation of longer storage life of solid-state systems, i.e., 5 years. (ICC regulations require that storage bottles be removed and proof pressure tested every 3–5 years.) 7) Simple, visual surveillance of each unit for condition of chlorate candle within the sealed container by use of inspection window. 8) Simple replacement of any unit, should it show any sign of deterioration, by plug-in cartridge, by relatively unskilled service crew; easily checked for installation and readiness for functioning from flight deck. 9) Programmed oxygen-release rates, irrespective of the type of emergency, whether it be unexpected cabin decompression or hard landing. (In the case of hard landing, additional advantages are gained: no possible bottle or line rupture, uniform distribution of the supply, and controlled low-pressure release in the event the unit is triggered and there is a fire. The last is probably one of the most desirable advantages of a solid-state system, since it avoids having an extremely fast burning hot spot fed by high-pressure gaseous oxygen, which will accelerate ignition of all combustibles. This feature also, if contributing to a local area fire, offers a lower order of extinguishing problem.) Figure 11 is illustrative of the state-of-the-art capabilities available from industry today. The unit pictured is about one-quarter size and supplies sufficient emergency oxygen for one person up to 30 min.

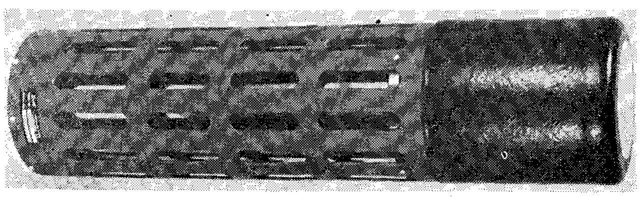

Fig. 11 Chlorate oxygen-generating unit (30-min supply for one man).

Certainly all pros and cons for the two systems are not discussed, but hopefully sufficient itemization is provided to encourage the aerospace engineers and scientists to either re-evaluate or consider the possibilities of developing simpler, more reliable systems. In all fairness it should be stated that the designers and manufacturers, fully supported by the Federal Aviation Administration and the military organizations, are flying and developing new systems which are demonstrating a high degree of safety for pilots and passengers equalled by none.

Conclusions

The following comments are not truly a conclusion or summary but rather a simplified restatement of objectives toward which it seems fundamentally necessary to work. As aircraft technology and performance capabilities progress, the designer and supporting technologies must make an ever increasing effort to improve the over-all performance, quality, reliability, and safety of oxygen systems by making fuller use of the technological developments in other fields.

References

[1] Madden, J. F., "Notes on Carbon Dioxide Elimination in Connection with Submarine Air Purification," NRL Rept. Sept. 1929, Naval Research Lab.

[2] Lamb, A. B., Bray, W. C., and Frazer, J. C. W., "The Removal of Carbon Monoxide from Air," *Journal of Industrial Engineering Chemistry*, Vol. 12, 1960, pp. 213–221.
[3] Brown, E. W., "Medical and Hygienic Aspects of the Submarine Service," *U.S. Navy Medical Bulletin*, Vol. 14, 1920, pp. 8–17.
[4] Carpenter, D. M., "Habitability of Submarines," *U.S. Navy, Medical Bulletin*, Vol. 26, 1928, pp. 31–40.
[5] Du Bois, E. F., "Review of Recent Work on Air Purification in Submarines," *Submarine Ventilation Bulletin No. 4*, March 1919, Bureau of Medicine and Surgery, Navy Dept.
[6] Miller, R. R. and Piatt, V. R., ed., "The Present Status of Chemical Research in Atmosphere Purification and Control on Nuclear-Powered Submarines," NRL Rept. 5465, April 1960, Naval Research Lab.
[7] Miller, R. R., "Alkali Metal Peroxy Compounds in Submarine Air Purification," NRL Rept. 5465, April 1960, Naval Research Lab.
[8] "Atmospheric Regeneration Aboard Submarines," Ionics Inc., Cambridge, Mass. Contract NObs-77048.

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A Vortex Method for the Study of Airplane-Missile Aerodynamic Interference

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Within the slender body theory, a vortex method is developed for the study of aerodynamic interference between a missile, in both captive and dropped positions, and the carrying airplane. In the crossflow plane, the airplane fuselage is approximated by a circle represented by a doublet; the airplane wing, pylons, and the missile wing panels are represented by evenly distributed vortices. The case of a cruciform missile carried underneath a vertical pylon or dropped therefrom on each side of the airplane is considered. The normal force, side force, and rolling moment on the missile are computed for a typical geometry. They agree with results obtained by electric analogy performed on conducting papers with cutouts identical to the present model. Ways of improving the present method in the light of results obtained by electric analogy, wind tunnel, and flight test of actual configurations are indicated.

Nomenclature

a = radius of airplane fuselage, ft
b = radius of missile fuselage at the base, ft
C_y = side force coefficient, $Y/(qS)$
C_z = normal force coefficient, $Z/(qS)$
C_l = rolling moment coefficient, $l/(qS\ 2b)$
d = airplane wing elevation, ft
e = horizontal pylon location from z axis, ft
f = location of lower edge of pylon from y axis, ft
g = horizontal missile location from z axis, ft
h = vertical missile location from y axis, ft
l = rolling moment, lb-ft
L = length of missile, ft
N = number of vortices representing the airplane wing panel
P = number of vortices representing the pylon
q = dynamic pressure, $\frac{1}{2}\rho_\infty U^2$, psf
Q = number of vortices representing each missile wing panel
S = cross-sectional area of the missile at the base, ft^2
s = semispan of airplane wing, ft
t = semispan of missile wing, ft
U = forward velocity of missile, fps
v = velocity component along y axis, fps
w = velocity component along z axis, fps
X = complex cross-flow plane, $y + iz$
Y = side force, lb
Z = normal force, lb
α = angle of attack, rad
Γ = strength of circulation, ft^2 per sec
γ = strength of vortex, ft^2 per sec
ρ_∞ = mass density of freestream, slug/ft^3

Subscripts

0 = uniform crossflow
1 = airplane fuselage
2 = airplane wing
3 = airplane pylon
4 = first quadrant wing panel of the missile on the right
5 = second quadrant
6 = third quadrant
7 = fourth quadrant

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Introduction

THE steady, irrotational flow over slender configurations at small angles of attack and of side slip may be treated by the slender body theory.[1–5] In essence, one deals with the Laplace equation in the crossflow plane subject to the boundary conditions on the body and far away from it. The validity of the theory is established by comparing results so obtained with more exact theory and experiments. The method of conformal mapping may be conveniently applied to simple shapes, such as plane- and cruciform-wing and body combinations. For complicated geometries, however, one does not always find the desired conformal transformations and must, therefore, resort to more approximate methods. One of these is the vortex method, treated independently by Nielsen[5] and by Campbell.[6,7] It was found[8] that Campbell's method is better suited for digital machine computation.

In Campbell's vortex method[6] for wing-body interference, the circular body is represented by a doublet in the uniform crossflow, and the thin wing panels by a finite number of evenly distributed discrete vortices. To maintain the shape of the circle as well as the constancy of flow circulation, one applies the method of images.[9] For each vortex introduced,