Journal of Spacecraft and Rockets

VOLUME 1 JULY-AUGUST 1964 NUMBER 4

Gaseous Environment during Space Missions

FRANK J. HENDEL
North American Aviation, Inc., Downey, Calif.

OXYGEN is more important to the survival of man than water or food. Man can survive for as long as two weeks without water or food, but without oxygen he can live for only a few minutes. In the spaceflights conducted to date, gaseous environments ranging from 3.5 psia of pure oxygen to the normal atmosphere at sea level proved to be satisfactory. These included spacecraft flights from 1 to 81 orbits (see tabulation in Ref. 26) and many X-15 and the two Mercury suborbital flights.

With respect to the more general problem of life support, graphs that show the launch weights of different environmental-control systems during long-duration missions (up to 1000 days) are available.[33, 61] Studies have indicated that for launch periods up to three months, launch-weight expenditure of 400 lb/man will provide for CO_2 removal, oxygen supply, and, if sufficient power is available, for water and oxygen reclamation; this weight expenditure (which does not include food) must be doubled for missions of one year and tripled for three-year missions. The material balance[33] for water, food, and oxygen, and the wastes that result from these intakes, indicate that slightly more water can be produced by the incineration of all metabolic wastes than is ingested. At the same time, the incineration method removes obnoxious gases from the gaseous environment. Biologistics, i.e., supply and resupply of the future manned orbiting stations (or laboratories) and lunar bases, may result in a considerable weight saving if the regeneration equipment is of an advanced nature, as shown by Mayo et al.[46] In general, the weight of equipment for such reclamation must be doubled if the station is to be supplied every 100 days instead of 30 days, as shown graphically by Wu and Yakut.[91]

In the present paper, recent work on the gaseous environment for spacecraft, with particular attention to oxygen management, toxicity, and environment selection, is surveyed.

Management of Oxygen

The methods for managing oxygen, in increasing order of complexity, are 1) open cycle, 2) physical separation, 3) absorption of CO_2 by expendable chemicals, 4) sorption of CO_2 by regenerable sorbents, 5) simultaneous absorption of CO_2 and production of oxygen, and 6) closed and semiclosed ecological cycles, which are represented by complete botanical systems (as yet undeveloped) and chemical systems, respectively. Each of these is surveyed in the sections below.

Oxygen can be stored either as a gas at room temperature and high pressure (optimum pressure with respect to weight and volume of gas, plus tanks, is 9500 psia) or in a cryogenic system.[60] The latter, which requires much smaller and lighter tanks, can be divided into subcritical and supercritical categories. Subcritical storage involves both liquid and gaseous oxygen. The presence of two phases in zero-gravity conditions leads to a requirement for pressurized (by helium) expulsion bladders to force the liquid oxygen toward the outlet. A compensating advantage is that liquid oxygen has the highest density under subcritical conditions, 1.142 gm/cm^3 at -297°F and 14.7 psia.

In "supercritical storage" in the beginning of the mission, oxygen is in the liquid form at -279°F and 900 psia (left of the dome on the enthalpy-pressure chart) and at a density of 71 lb/ft^3. At this pressure, the initial small ullage filled with vapors of oxygen fully disappears, so that the fluid in the tank is in one phase. As the oxygen is being removed from the tank, the fluid is progressively heated by electrical heaters to the critical temperature (-182°F) at which

Dr. Hendel is a staff scientist with Apollo Space Sciences and Systems. He has been associated with projects Apollo, Nuclear Saturn, Space Station, Lunar Base, and Martian Spacecraft. Prior to joining North American Aviation, Inc., Space and Information Systems Division, in 1961, he was associated with Aerojet General Corporation, Azusa, Calif., where, since 1956, he worked as senior engineer, project manager, and head of the chemical engineering section. Dr. Hendel is an Associate Fellow Member of AIAA, and a member of AIChE, ACS, ANS, AMA, and AOA. He is the author of numerous publications on gaseous environment and water recovery during space missions and is an active contributor to *Chemical Abstracts*. In 1962–63, he was a consultant to the Gaseous Environment Group of the National Academy of Sciences, Space Science Board. He also teaches courses in space vehicles, missiles, and aerospace technology at the University of California, Los Angeles, and in two colleges. He has recently written a two-volume textbook titled *Rocket and Aerospace Technology*.

Received September 24, 1963; revision received April 27, 1964. The many suggestions by G. C. Clementson, Director, Space Sciences, Apollo Program, Space and Information Systems Division, and by my wife, which were incorporated into this paper, are gratefully acknowledged by the author.

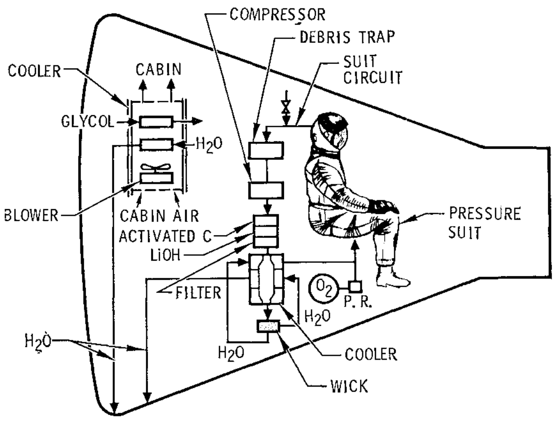

Fig. 1 Thermal and atmospheric control.

the liquid phase is fully changed into the gaseous phase; this occurs when approximately 40% of oxygen has been removed. Eventually the temperature is increased to 100°F. Thus, by keeping the pressure in the tank above the critical pressure, which is 730 psia, there is only one phase, either liquid or gaseous, and the problem of two phases in zero gravity is avoided.

These direct methods for storing this fluid can be used to some extent in any oxygen management system (except the closed ecological cycle). There are also chemical methods by which oxygen can be generated as needed, e.g., from water, the thermal decomposition of sodium chlorate candles, or hydrogen peroxide. Electrolysis[48] is used in many of the oxygen management systems discussed below, but the chlorate candles and H_2O_2 would be used only as open-cycle sources.

Open Cycle

This method, in which the exhaled air is dumped overboard, is limited to missions of short duration, such as the X-15 rocket plane. As was just noted, oxygen for open-cycle systems may be stored either as such or in chemical compounds that can be decomposed to generate it as needed. For example, the exothermic decomposition of sodium chlorate,[7] $NaClO_3 \xrightarrow{1300°\text{-}1500°F} NaCl + 3/2\ O_2$, produces approximately 40% oxygen by weight and releases approximately 600 Btu/lb of oxygen liberated. The burning rate is 0.32 to 0.46 in./min, independent of the pressure up to 500 psia. The mixture contains a binder, a small amount of iron powder, and barium peroxide (4 to 5%). The oxidation of the iron powder liberates sufficient heat to maintain the burning, and the barium peroxide takes out the free chlorine formed by a secondary reaction; a Hopcalite catalyst bed also removes chlorine and the CO formed by the binder.

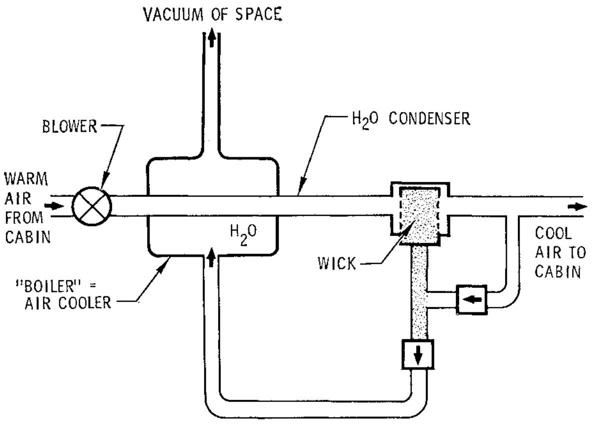

Fig. 2 Evaporative cooler ("boiler").

The oxygen is filtered through fiberglass to remove the smoke of sodium chloride.

Chlorate candles have been used as emergency equipment on submarines and aircraft. The densities of cast and pressed candles are 0.082 and 0.076 lb/in.[3], respectively. They would be useful on space missions for emergencies only.

Hydrogen peroxide, widely used as a monopropellant for attitude control and secondary power generation, could also be used as an oxygen supply.[35] When liquid H_2O_2 (90 to 98% in strength) is forced through a tube filled with silver-gauze, it decomposes exothermally to water and oxygen. After cooling, the water is separated from the oxygen, which amounts to 0.47 lb/lb of H_2O_2. Approximately 6.5 lb of hydrogen peroxide and equipment are required per man-day. Because of this high weight and the high heat release (2610 Btu/lb of oxygen liberated), H_2O_2 would probably be used only as a supplementary oxygen source, e.g., whenever heat is required to warm food, heat water, raise the temperature in the space cabin, or prevent rocket propellant from freezing.

Physical Separation

Semipermeable membranes

Membranes of this type are suggested[31] for the separation of CO_2 from oxygen. The following expressions (derived from Frick's law) may be applied:

$$P = P_0 e^{-E_p/RT} \qquad E_p = E - \Delta H_s$$

where P is the permeability coefficient, P_0 the reference permeability coefficient, E_p the permeability activation energy, T the membrane temperature, E the diffusion activation energy, and ΔH_s is the heat of solution of gas in the membrane material. Reference 31 reports that certain additives to the membrane material resulted in a 2000-fold change in the permeability.

CO_2 freezeout

The freezeout method, although not yet applied, is of interest for spacecraft that have cryogenic O_2, N_2, or H_2 heat sinks. A good countercurrent heat exchange between the environmental exhaust gas and the cryogenic gas is mandatory. First the water and then the CO_2 will freeze out. A temporary stopping of the cryogenic gas will cause the CO_2 and ice to warm; the CO_2 will sublime and can be dumped overboard, and the ice will melt to water. By this technique, nearly all other contaminants of the gaseous environment can be removed.

Absorption by Expendable Chemicals

Many solid chemicals will readily absorb CO_2 from the air, but lithium oxide and the two forms of lithium hydroxide have the lowest molecular weights (approximately 30, 24, and 42, respectively). The chemical reactions involved are

$$\begin{aligned} Li_2O + CO_2 &= Li_2CO_3 \\ 2LiOH + CO_2 &= Li_2CO_3 + H_2O \\ 2LiOH \cdot H_2O + CO_2 &= Li_2CO_3 + 3H_2O \end{aligned}$$

The first two occur readily, provided that the processed gas contains water vapors. All three are exothermic; the second, which is widely used for CO_2 removal in manned spacecraft, produces 875 Btu/lb of absorbed CO_2, assuming that the water is evolved as vapor. (Tests have shown that, under normal operating conditions, practically all of the water is vaporized.) Usually, the efficiency of removal of CO_2 by this method exceeds 70% until the "breakthrough" point, at which the CO_2 concentration in the effluent gas reaches a specified value. (Typically, a CO_2 partial pressure of 8 mm Hg is attained.) Utilization efficiencies of 95% are attainable. For a CO_2 exhalation rate of 2.25 lb/man-day, 2.52 lb

LiOH/man-day will be required; the over-all weight with packaging is approximately 2.7 lb/man-day. The bulk density of granular LiOH is between 0.0145 and 0.0162 lb/in.^{3} (The density of crystals is 0.092 lb/in.^{3}.) Spent LiOH, which contains a high percentage of lithium carbonate, can be regenerated by heating it to a temperature above 1200°F.

Figure 1 depicts a LiOH system for thermal and atmospheric control[73] which is similar to that used in Mercury flights. In the pressure-suit circuit, the exhaled gases are sucked through a debris trap and a replaceable canister containing a layer of activated carbon (for odor removal), LiOH for CO_2 removal, and a filter. The gas then goes through a two-part cooler; one part, called the "boiler" (Fig. 2), is cooled by evaporating water into the vacuum of space, and the second part is cooled by a cold glycol-water solution or cooling oil. The water condensed from the gas stream is trapped by a wick that transfers the water to storage by capillary action. The dry gas stream is warmed by exchanging heat with the warm gas from the LiOH canister. Gaseous oxygen is constantly added to the circuit. The suit works continuously, whether the visor is kept open and the astronaut is exposed to the cabin environment (in the cases of Mercury, Gemini, and Apollo, the environment consists of 100% oxygen at 5 psia), or the visor is closed and the suit is pressurized to 5 or 3.5 psia with 100% oxygen. If the pressure suit is removed from the circuit, the cabin air will be purified. The cabin circuit consists only of a blower that moves the cabin air oxygen through a boiler and a glycol cooler. The warm glycol is cooled in a space radiator.

Sorption by regenerable sorbents

Silver oxide is a *chemical absorbent* for CO_2 at room temperature:

$$Ag_2O + CO_2 = Ag_2CO_3$$

(The silver oxide is easily regenerated by heating to 250°F and venting to vacuum.) The reaction is slightly exothermic, producing 151 Btu/lb of CO_2 absorbed. Its theoretical capacity is 0.19 lb CO_2/lb Ag_2O, but it may deteriorate because of a slow decomposition to metallic silver which takes place at elevated temperatures:

$$Ag_2O = 2Ag + \tfrac{1}{2}O_2$$

Another chemical method employes the electrodialysis principle similar to the one suggested for water recovery.[33] Air is blown through an electrodialysis cell where CO_2 is combined with a hydroxide compound, forming a carbonate and water. The carbonate and the hydrogen ions, after passing through a selective membrane into certain compartments, form carbonic acid, which bubbles out as concentrated CO_2. The problem in this procedure lies in the formation of small amounts of hydrogen that must be removed from the atmosphere.

Physical sorption of CO_2

This can be accomplished by synthetic zeolites that are crystalline alumino silicates of alkali and alkaline earth metals.[18] These materials, known commercially as "molecular sieves" (Linde Company) or "microtraps" (Davison Chemical Company), are characterized by a large number of channels of regular diameter in the crystal lattice. The diameter of these channels can be varied by changing the nature of the ion associated with the alumino silicate group. The size, number, and shape of these pores determine the affinities of the sieves to certain gases and liquids.

Unfortunately, those materials used for CO_2 have an even greater affinity for moisture. To achieve a continuous cycling of the CO_2 removal beds, the humidity must be reduced to ~10 ppm by a dessicant, which may be either silica gel or a special molecular sieve 4AXW (a Linde designation). In the adsorption cycle (Fig. 3), the dessicant becomes saturated with moisture and the molecular sieve retains CO_2. The air (or oxygen), freed from moisture and CO_2, is heated to 350°F (Fig. 3b) and passed through the dessicant bed to regenerate it by evaporating the moisture. When the air is cooled, the moisture condenses and water is recovered. The CO_2 sieve is regenerated by heating it to ~380°F and subjecting it to a vacuum of 27 to 29.5 in. Hg to recover pure CO_2 (Fig. 3d). If the recovery of either CO_2 or water is not necessary, the regenerations are accomplished simply by venting the beds to the vacuum of space (Fig. 3c). This adsorption and regeneration system has been developed by Hamilton Standard, Division of United Aircraft Corporation.[44] The absorption unit during a 3-man, 14-day mission with pure oxygen at 5 psia will weigh 50 to 52 lb.

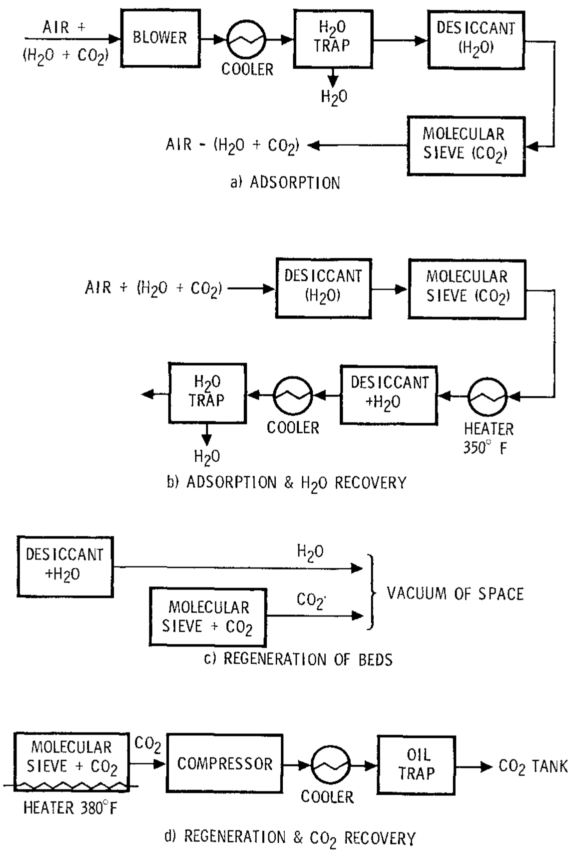

Fig. 3 H_2O and CO_2 removal.

Absorption of CO_2 and Oxygen Production

Solid superoxides of potassium or sodium absorb CO_2 and release oxygen.* The presence of water vapor and a catalyst (heavy metal oxide) is mandatory. The main reactions (all exothermic) for the KO_2 system are

$$4KO_2 + 2H_2O = 4KOH + 3O_2$$

$$4KOH + 2CO_2 = 2K_2CO_3 + 2H_2O$$

$$2K_2CO_3 + 3H_2O = 2K_2CO_3 \cdot 3H_2O$$

With moderate physical activities and a 3000 kcal diet, a man will consume daily about 2.0 lb of oxygen and generate 2.25 lb of CO_2 and 2.3 lb of water vapor. The astronauts' "respiratory quotient" (R.Q., defined as the volume ratio of

---

* Potassium or sodium peroxide also releases oxygen (or H_2O_2) when reacted with CO_2 (or water, respectively), but peroxides generally release less O_2 than do superoxides.

CO_2 formed to oxygen consumed) would be 0.82 for this metabolism. In comparison, for the potassium superoxide reactions, the chemical R.Q. $= 2CO_2/3O_2 = 0.67$, so that there would be an underabsorption of CO_2 for the required oxygen level. Thus, an additional means for partial removal of CO_2 becomes necessary. This supplement could be a canister of LiOH (as in Fig. 1), but to balance fully the absorption of CO_2 and release of oxygen, a partial conversion of the carbonates to the bicarbonate

$$K_2CO_3 + CO_2 + H_2O = 2KHCO_3$$

can be used. (If this reaction were used in full, the chemical R.Q. would be 1.33.) This reaction is more easily accomplished in the sodium superoxide system, which also is lighter because of its lower molecular weight, but its volumetric efficiency is lower and its heat release higher. (The commercial form of KO_2 develops 675 Btu/lb O_2 liberated, and that of NaO_2, 810 Btu/lb.) With NaO_2, $\sim$5 lb/man-day, including the weight of the canister, is required. Lithium superoxide (LiO_2), which is now under investigation, could reduce this weight to perhaps 4 lb/man-day. These weights are slightly less than the weight of the LiOH plus cryogenic oxygen system ($2.7 + 2.5 = 5.2$ lb/man-day, including tankage), but the required heat-dissipation values necessitate approximately 20% heavier equipment. Other advantages of the superoxide system are its smaller volume and its ability to remove toxicants that are easily oxidized. For instance, CO is removed by

$$2NaO_2 + CO = Na_2CO_3 + O_2$$

Also under consideration at present are such compounds as calcium superoxide and ozonides of potassium, sodium, and lithium. Table 1 summarizes oxygen production from chemicals.[58, 59]

The sodium superoxide method has been ground tested by NASA[21] in a 5-man, 30-day life-support system devised by the Boeing Company. Bottled nitrogen is used to maintain a 21/79 mixture of gases at sea-level pressure. A large chamber simulates quarters on a space station or at a moon base. Its equipment also provides waste disposal and water recovery. Special (but varied) diets of freeze-dried food, some of it in squeeze tubes, include shrimp, strawberries, and peanut-butter sandwiches. Specific crew tests include space navigation, scope reading, tracking, time estimating, decision making, and attention span. Psychologists observe the crew through a one-way window. A support crew constantly analyzes bacteria and toxic compound buildup within the gaseous environment.

Table 1 Chemicals ranked by oxygen content

Formula	Generic name	O_2 avail., weight percent	CO_2 pickup	Developed
LiO_3	Ozonide	73	Yes	No[a]
H_2O_4	Superoxide	73	No	No[a]
LiO_2	Superoxide	61	Yes	No[a]
$LiClO_4$	Perchlorate	60	No	No
$Mg(ClO_4)_2$	Perchlorate	57	No	No
NaO_3	Ozonide	56	Yes	No
$Ca(ClO_4)_2$	Perchlorate	54	No	No
$NaClO_4$	Perchlorate	52	No	No
H_2O_2	Peroxide	47	No	No
$LiClO_4 + Li_2O_2$	(Mixture)	47	Some	Nearly
KO_3	Ozonide	46	Yes	No
$Ca(O_2)_2$	Superoxide	46	Yes	No
$KClO_4$	Perchlorate	46	No	No
NaO_2	Superoxide	43	Yes	Yes
H_2O_2, 90%	Peroxide	42	No	Yes
$NaClO_3$	Chlorate	40	No	Yes
Li_2O_2	Peroxide	35	Yes	Nearly
KO_2	Superoxide	34	Yes	Yes

[a] Distant future.

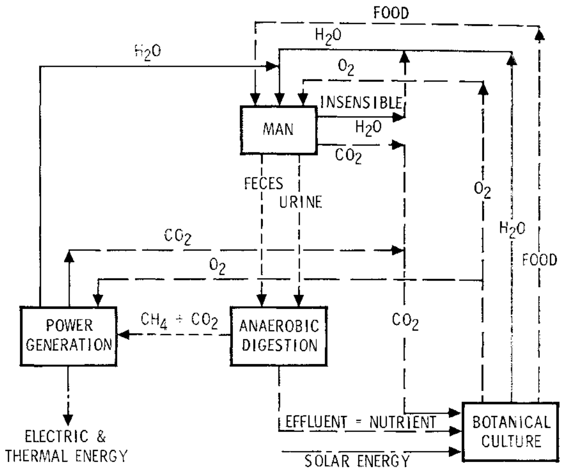

Fig. 4 Integrated closed ecological system.

Closed and Semiclosed Ecological Cycles†

A fully closed ecological cycle may be a botanical cycle in which all of man's wastes are utilized by plant life and completely regenerated as oxygen, food, and water. The only additional energy is supplied by the sun. A system is being investigated for spacecraft application, using algae or higher plants for the absorption of CO_2 and the generation of oxygen and food (a photosynthetic system). A fully closed ecological system is difficult to achieve, but chemical methods can be used to obtain semiclosed ecological systems.

Closed botanical systems

Much work is being done on the algal system, higher-plant system, and combinations of the two.[13, 14, 28, 29, 45, 55] These systems are based on the photosynthetic absorption of CO_2 and water to form oxygen and organic materials (such as glucose or hexose), which requires a large surface area illuminated by sunlight. Artificial illumination, as practiced now in laboratories, will perhaps be practical only on a moon base with a nuclear power generation station. The reaction that takes place in a photosynthetic gas exchanger is

$$6CO_2 + 6H_2O + 677 \text{ kcal} = C_6H_{12}O_6 + 6O_2$$

Theoretically, photosynthesis is a solution to the over-all problem of life support. However, man cannot consume all the algae that will have to be harvested continuously,‡ and some of the CO_2 and H_2O will be lost as stored organic compounds in the extra algae.

Since only 0.07% of algae (dry basis) can be suspended in water, the algal suspension requires 220 to 500 lb of water per man, which is prohibitive for short missions. Another inherent problem is the possibility of sickness of the algae, which often occurs, reducing the reliability of the system. As

---

† A closed gaseous environment system is often erroneously called a closed ecological system, but, in space technology, only that system which utilizes living organisms for CO_2 absorption, generation of oxygen, and production of food is properly so termed. A system used only to purify and generate oxygen in a closed environment should be called a closed respiratory circuit.

‡ Poultry or rabbits should be utilized as "middle men" in feeding humans with algae. North American Aviation is constructing three $\frac{1}{5}$-acre ponds where unprocessed waste will be utilized for growing 10 tons/year of algae of high protein content. The algae, when harvested, will be blended with a standard chicken feed. Similar ponds may be used on a lunar base (provided that they are covered with a transparent structure that will protect them from the lunar vacuum).

suggested by J. C. Finn (North American Aviation, Inc.; private communication), higher plants can be used in a system of greater over-all weight. Figure 4 shows a fully closed ecological system integrated with power generation. In the over-all balance, the solar energy is changed into electric and thermal energies. This system uses anaerobic digestion of human wastes.

A combination of chemosynthesis, electrolysis, and biosynthesis for space applications has been suggested by Bongers.[9] Electrolysis of water yields hydrogen and oxygen, which are then utilized with CO_2 by a culture of Hydrogenomonas to form food. The excess of oxygen from the electrolysis is used for respiration. It is indicated that 20 liters of culture and 1 kw are required per man.

Akerlof[2] suggests the exposure of CO_2 and of hydrogen to a high-temperature glow which is obtained from a direct current discharge at subatmospheric pressures. The resulting CO is mixed with an additional amount of hydrogen and exposed to a silent discharge forming formaldehyde. The latter can be condensed at moderate temperature to formose sugar.

Chemical semiclosed systems

Several methods are discussed below. Logistics and reliability of a variety of these have been discussed by Bialecki.[6] First is the *Sabatier reaction*, also called the "methane-producing reaction" or "methanation," in which hydrogen is used for the catalytic reduction of CO_2 to methane (or other hydrocarbons) and water:

$$CO_2 + 4H_2 = CH_4 + 2H_2O + 1600 \text{ Btu/lb of } CO_2$$

This reaction has been used for many years in industry. At fairly low temperatures (320° to 470°F), it gives high efficiencies, from 97 to 99.8%. The methane produced is vented overboard, and the water vapor is absorbed (e.g., in a P_2O_5 cell) and electrolytically decomposed to H_2 and O_2. Figure 5 is a schematic system for three men. Carbon dioxide, desorbed, from the molecular sieve (Fig. 3) and stored at 15 psia,[1] is mixed with H_2 from the electrolytic cell and passed through the catalytic reactor, which is initially heated to 450°F. The catalyst is nickel or ruthenium, supported by diatomaceous earth or alumina.[17] The methanation reaction is exothermic; hence, the reactor has to be continuously cooled. The effluent goes through a cooler to condense and separate water. Additional makeup water, which may exceed 30% of that necessary to produce enough oxygen and hydrogen, is required because 1) oxygen is used in the metabolic processes to produce both CO_2 and water, and 2) there is some loss of oxygen through the leaks in the wall of the space cabin. The makeup water can be obtained from the distillation of urine, from sensible water recovery, from fuel cells, or from stored water supply. The electrolysis theoretically requires 1600 w-hr/lb H_2O; this restricts the use of the Sabatier system to situations where electrical energy is available in great quantity [e.g., when a large SNAP-type system (Nuclear Auxiliary Power) is aboard].

A variation of the Sabatier reaction being developed by TAPCO division of TRW, Inc. and General Dynamics/Astronautics (data from G. L. Drake) is the industrial "water-gas" (Bosch) reaction.[3] When CO_2 is reacted with hydrogen at 1350°F in the presence of a catalyst, water vapor, carbon, and CO are formed. The latter is further decomposed in a catalytic reactor to CO_2 and graphite ("producer gas" reaction in reverse). Solids are removed by a scraper.

The *methoxy system*[64] uses the Sabatier reaction and the electrolysis of water, but the methane produced is pyrolyzed at high temperature to form solid carbon and gaseous hydrogen. Without a catalyst, 97% efficiency is achieved at 2200°F; with a nickel catalyst support on alumina, 100% conversion is achieved at 1920°F. The carbon is stored as waste, and the hydrogen is used in the Sabatier reactor. This system is shown by the dotted line in Fig. 5. The development of this method is hampered by the high energy requirement and the difficulty in removing the hard, compact, amorphous carbon deposits on the catalyst.

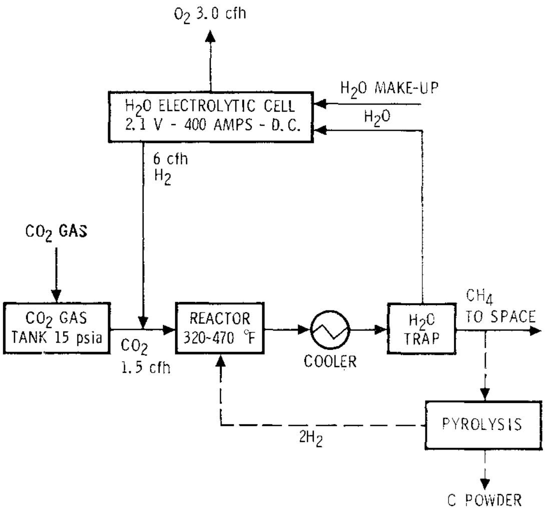

Fig. 5 Sabatier system for three men.[1]

The *electrocarb system*[64] uses an electrolytic cell containing a fused mixture of alkali and alkaline earth carbonates. The electrodes enter the cell through two hollow zircon tubes that dip into the fused electrolyte. CO_2 is supplied under pressure to the cathode. A d.c. potential of 2 to 5 v produces CO at the cathode and CO_2 and oxygen at the anode. The CO is circulated through an iron carbide catalyst bed at 750°–900°F to convert it to carbon and CO_2. The CO_2 is recycled to the cathode. The problems of separation of oxygen from CO_2, the toxicity of CO, the high energy requirements, and the deposition of carbon (graphite) on the catalyst make utilization of this system unlikely for spacecraft.

A different approach is used in the *photolysis* system. Under ultraviolet light, CO_2 changes into oxygen and carbon monoxide. The carbon monoxide will change in the converter into graphite and CO_2 which will go back to the ultraviolet photolysis. The problems inherent in photolysis are similar to those of the electrocarb method.

Another approach is based on the *electrolysis of lithium carbonate.*[74] In this system, CO_2, under pressure, is absorbed in a molten lithium salt mixture containing a eutectic of lithium oxide, fluoride, and chloride, and the lithium carbonate formed electrolyzed at 1000° to 2000°F, evolving O_2 at both the anode and cathode:

$$\begin{array}{ll} & C + \tfrac{3}{2}O_2 + 2e^- \\ & \nearrow \\ CO_3{=} & \\ & \searrow \\ & CO_2 + \tfrac{1}{2}O_2 + 2e^- \text{ (parasitic reaction)} \end{array}$$

$$Li^+ + e^- \rightarrow Li \xrightarrow{Li_2CO_3} \tfrac{3}{2}Li_2O + C + \tfrac{3}{4}O_2$$

The over-all reaction (neglecting the parasitic one) is

$$Li_2CO_3 \rightarrow Li_2O + C + O_2$$

The electrolysis was carried out by Shearer[74] using stainless-steel equipment and a current density of 1.7 to 1.96 amp/cm^2 at the cathode. The problems in this system are corrosion, the high temperature required to release oxygen, the small amount of CO in oxygen, and the accumulation of carbon in the electrolyte. A mathematical analysis to minimize the weight of this system has been made by Davis and Novosad.[23]

Another method employs *lithium hydride* to form LiOH, which is then electrolytically decomposed at 750°F:

$$2LiH + CO_2 = 2LiOH + C$$

$$2LiOH = 2LiH + O_2$$

Some of the problems are 1) an undesirable secondary reaction between LiOH and Li, forming H_2, which is insoluble in the electrolyte Li_2O, 2) the physical removal of carbon from the molten electrolyte, and 3) the liquid-liquid separation of Li from LiOH in the centrifugal separator to minimize polarization losses.

Carbon dioxide can also react with *metallic sodium* (or another alkali metal) to yield Na_2O and carbon. With water, Na_2O will give NaOH, which, when electrolyzed (e.g., in commercial Castner cells), at above 600°F will yield oxygen, hydrogen, and metallic sodium. According to Konikoff,[40a] cell voltage of 8 and a current density of 2 amp/cm^2 give high yields.

The pyrolysis of CO_2, a highly endothermic reaction,[35, 66] can be achieved by blowing the CO_2 (desorbed molecular sieve) through an electric arc to produce $C_{(g)}$ and O atoms. Quenching to a low temperature prevents recombination to CO_2. The carbon can then be filtered out, briquetted, and stored, while the recovered oxygen undergoes additional purification in a Hopcalite reactor to remove traces of CO. This method has not yet been developed, but, if it were, the required high-energy input could come from SNAP-type atomic reactors or from solar collectors.

Oxygen Recovery on the Moon

A moon base probably will depend on oxygen recovered from a closed ecological cycle and/or from moon minerals and moon ice. If the moon base is provided with a nuclear reactor for power generation, it will have ample energy to melt ice and electrolyze water (the H_2 could be used as a rocket propellant). Rocks in the earth's crust contain from 1 to 12% chemically bound water and/or water of crystallization, and it seems likely that similar percentages will be found on the moon, at least in shallow, subsurface layers. Lunar water sources may be as follows: chemically bound water present in the volcanic extrusives, ice in permanently shadowed zones in volcanic fractures and fissures, water of crystallization in volcanic sublimates, permafrost in dust basins, and water in carbonaceous chondrites and other rock types.[34]

Since the pressure of the lunar atmosphere may be as low as 10^{-13} mm Hg, ice would vaporize even at -150°C, but it may be possible that in fractures and fissures the pressure is considerably higher (possibly from radon gas leakage). Under its surface, half of the moon may be dirty ice; this could account for its low mean density of 3.3 (compared to 5.5 for earth). Professor Zdeněk Kopal (Department of Astronomy, University of Manchester, England) in a private communication, noted his opinion that small domes (a few km in diameter and 100–200 m high), which appear on the lunar surface in clusters, are connected by underground layers of ice.

The lack of atmosphere permits not only macrometeorites but also the micrometeorites to fall from "dusty" space into the moon. These meteorites are assumed to be of the same composition as those falling on earth: chondrites and achondrites (90%), and irons and stony irons (10%). Chondrites and achondrites contain approximately 33 and 50% SiO_2, respectively. Generally, their water content is very low ($\sim$0.1%), but some of the chondrites are carbonaceous and contain a remarkable amount of water, up to 16%.

It is possible that all meteoroids in space are carbonaceous and have high water content. One present theory holds that the nucleus of a comet is composed of frozen water, methane, and ammonia (which hold together the stones, irons, or stony irons found in meteoroids), and that when a comet approaches the sun, a small part of the methane vaporizes, thus causing the partial disintegration observed as the comet's "tail." The intense electromagnetic and corpuscular radiation near the sun catalyzes reactions between CH_4, NH_3, and H_2O, forming such free radicals as C_2, CH, OH, NH_2, NH, and CN, which have been found in the spectrum of comets' tails. The energetic free radicals probably form carbon, organic materials, water, and silicates, such as olivine, pyroxene, orthopyroxene, enstatite, hyperstene, and ferroaugite. Particles from comets' tails account for most of the meteoroids in the solar system. When they reach the earth or the moon (they are then called meteorites), they may retain part of their original composition, depending on the heat of re-entry through the earth's atmosphere or on velocity at impact with the moon. The meteorites, especially the larger ones, at impact with the moon are mixed with ultra-basic rocks, which may contain serpentine (12.7% water). Polarization curves of lunar light, obtained by checking the polarization during different phases of the moon, show that maria are covered with a material similar to ocherous limonite, which contains ferric hydroxide and clay, and that the highlands are covered with ash tuff. All of these materials may be regarded as sources of water and oxygen.

Toxicity in a Closed Respiratory System

The gaseous environment in a space cabin can become polluted from a variety of sources.[10, 36, 69, 70, 77] Sixty toxic compounds have been detected, most of them originating from the outgassing from equipment, paints, putting compounds, and supplies stored aboard or used in the prelaunch stage (e.g., Freon 114[43] used for cooling the cabin through the umbilical tube). Quattrone[62] reported the following average levels of contaminants (given in ppm) in the recent Mercury flights: Freon 114 ($C_2Cl_2F_4$) 200; ethylene dichloride, 40; toluene, 20; n-butyl alcohol, 4; vinyl chloride, 3; ethyl alcohol, 3; m-xylene, 3; benzene, 1; formaldehyde, 1; and fifty other compounds at <1 ppm. Additional contaminants are produced by fires or local arcing or sparking. During a major fire that occurred in a ground-confinement test, Weber[83, 84] reported 400 contaminants, the major ones being CO_2, CO, acetaldehyde, acetone, ethyl alcohol, benzene, and acetylene. During sparking, arcing, or local fires in an O_2-N_2 atmosphere, traces of nitrogen oxides can be found.

"Pure" oxygen, which is stored under supercritical, cryogenic conditions, may contain traces of acetylene and methane. Once in space, the stored oxygen, under bombardment by energetic corpuscular radiation (galactic cosmic rays or energetic solar protons), may form traces of toxic ozone and ions.[38]

The human body defends itself from toxic compounds by 1) excretion and elimination (sometimes up to 75% of the introduced compounds are eliminated by these processes), 2) formation of detoxication conjugates, and 3) detoxication by other body actions. Only the remainder of the toxic compound will cause an observed toxicity. Some toxicants, when introduced into the body at the same time, show increased toxicity (synergism); others may become less toxic and even annihilate each other by chemical or physiological action (antagonism). The "threshold limit values" (TLV) or "maximum allowable concentration" (MAC) often may be too high for a man who has been exposed to a toxicant before and has a lower tolerance; i.e., if he has already had some damage to his organs, skin, or lungs, he may have become sensitive to that toxicant. Stokinger[78] suggests a formula for closed-circuit respiratory conditions, based on extrapolation of the industrial TLV:

$$\mathrm{TLV}_{\text{space cabin}} = \mathrm{TLV}_{\text{industrial}} \times (F_1/F_2 \cdot F_3 \cdot F_4 \cdot F_5 \cdot F_6 \cdot F_7)$$

where

F_1 = total pressure factor (e.g., for 5 psia, $F_1 = 14.7/5 \cong 3$)
F_2 = toxicant factor; suggested 1–4 (the highest is for ozone)
F_3 = temperature factor; suggested 2–3 (the toxicity is always the least at 78°F, whereas at lower and higher temperatures it is higher)

F_4 = disorientation (tumbling, etc.) factor; suggested 1–1.5
F_5 = oxygen concentration factor; suggested 2–4 (the highest is for 100% O_2)§
F_6 = fatigue, monotony, and anxiety factor; suggested 2
F_7 = factor depending on synergistic effects of other factors; suggested value, 2–5

Extrapolation of such values may not be as proper as finding TLV and MAC values by testing small animals, but toxicity values exhibited by small animals may be different from those for humans. Certain conjugations occur in men and dogs, for instance, that do not in cats, etc.

Aerosols can be harmful; maximum retention occurs when the particles are approximately 3μ. Below 1μ the particles are so small that their deposition (and, hence, retention) is very light, especially in the lower respiratory tree. Microbiological contaminants may also be present in the cabin air.[37] Ions are always present, and if their total concentration exceeds $1000/\text{cm}^3$ they can be considered to be contaminants, because they affect man both physiologically and psychologically.[16] Positive ions are produced by fluorescent lighting, high-voltage electronic equipment, radioactive dials, open flames, and radiations. Usually, aerosols decrease ion concentration by capturing them. A grounded, fine metallic mesh of 5μ, placed over the entrance or exit of a charcoal (activated carbon) filter, will remove ions.

A catalytic burner used for the oxidation of trace contaminants, including H_2 and CO, can produce additional trace contaminants if some of the organic compounds are only partly oxidized. Such a burner must be followed by a charcoal filter. The same type of situation can occur if a thin layer of chromium or molybdenum oxides is deposited on the charcoal during the absorption and oxidation of trace contaminants. The catalytic burners, referred to as Hopcalite catalytic units, are extensively used in submarines. Hopcalite is a trade name for a coprecipitated mixture of manganese and copper oxide, which accelerates the reaction of CO and O_2 to CO_2. At 650°F, it catalyzes the combustion of hydrocarbons, organics, and hydrogen with efficiencies from 80 to 100%, but methane conversion is very low (5 to 20%). Sulfur and nitrogen compounds are converted to oxides, and Freon is converted to the dangerous hydrogen fluoride. The catalyst must be kept always above 350°F to prevent the corrosive action of water vapor and to prevent absorption of unreacted hydrocarbon, which may cause an explosion.

Selection of the Gaseous Environment[85]

Naturally, environmental conditions simulating those on earth (air at 14.7 psia) would be desirable for long missions. The Russians used such an atmosphere in their manned Vostok.[75] Such a system, however, has numerous drawbacks: 1) the high pressure causes a greater leak rate through the walls, which imposes a weight penalty; 2) the wall structure also must be heavier due to the greater differential pressure; 3) the valving needed to control the two-gas system is more complicated than that required for a simpler system; 4) the over-all reliability is reduced because of the greater complexity in instrumentation—the system must measure and control both oxygen partial pressure p_{O_2} and total cabin pressure p_t. Regulation of the partial pressure of gases, appropriate testing, and instrumentation have been described in recent references.[11, 36, 51, 42, 52, 60, 79] There are several alternate atmospheres now employed which use pressure below 14.7 psia.

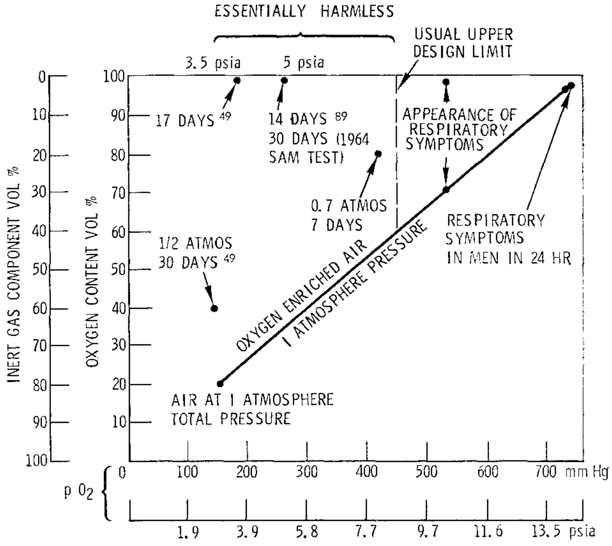

Fig. 6 Suitability of oxygen partial pressure.

For these, consideration must be given to the following abnormal conditions[76]:

1) Hypoxia,[25] when $p_{O_2} < 3.0$ psia (see below)
2) Anoxia, when $p_{O_2} = 0$
3) Hyperoxia,[5, 67] when p_{O_2} is high
4) Dysbarism, a decompression sickness (includes bends)
5) Aerotitis media, the inflammation of the middle ear
6) Pulmonary atelectasis, a partial lung collapse at low p_t and high g stresses
7) Ebullism, the boiling of body fluids at $p_t < 0.9$ psia

Figure 6 shows suitable p_{O_2} ranges.[53, 80] The upper design limit for continuous exposure is 9 psia (460 mm Hg); hence, with $p_t = 14.7$ psia, air may be enriched up to 60% O_2 with no harmful effects. At lower total pressures, oxygen enrichments above the sloping line and to the left of the upper design line have been found safe. Hyperoxia can occur at higher enrichments; oxygen will fill all of the body cavities; if it then becomes occasionally deficient, the body will absorb the oxygen from its own cavities and lower the internal pressure, which can produce pain or irritation in rigid surrounding members, such as the sinuses or middle ears, or lead to the collapse of softer surroundings, such as the alveoli of the lungs. The lower limit of oxygen partial pressure should be between 3.0 and 3.5 psia, depending on the presence or absence of an inert gas; the higher figure should be used for pure oxygen (problems of oxygen toxicity have been extensively reviewed[24, 65]). A p_t = 5-psia system is preferred, because the additional pressure assists in the ventilation of electronic equipment within the cabin and, in the event of a wall puncture by a meteoroid, provides significant protection against dysbarism.

In tests performed at U.S.A.F. School of Aerospace Medicine (SAM), at U.S. Navy Air Crew Equipment Laboratory, and at Republic Aviation Corporation, many subjects were confined for from 14 to 30 days in an atmosphere of pure oxygen at 3.5 and 5.0 psia.[32, 49] Some of the subjects experienced minor disorders—up to 7.6% reduction in vital capacity, eye irritation, substernal pain, cough, sore throat, joint or muscle pain, pulmonary atelectasis, ear discomfort (aural atelectasis), paresthesia (cold sensation, flushing or tingling of extremities), kidney pathology, and slight anemia—but it was definitely established that man can tolerate a 5-psia pure-oxygen atmosphere for at least 30 days (recent tests at SAM).

It has been proved (and applied in Mercury, Gemini, and Apollo spacecraft) that man can withstand the highest acceleration (or deceleration) forces in a transverse-supine position[82] also called "eyeballs-in," "back-to-chest," or "$-G_x$"

---

§ It is possible that the presence of nitrogen in the air has an additional beneficial effect by forming a layer in alveoli which acts as a filter for the toxicants. When oxygen molecules are being absorbed by the blood, the concentration of nitrogen molecules in the alveolar region temporarily increases, forming a protective blanket.

Table 2 Single-gas vs various two-gas atmospheres

Effects	Pure O_2 at 5.0 psia	50-50 mixtures (by vol.) at 7.0 psia		
		$O_2 + N_2$	O_2 + He	O_2 + Ne
Simplicity in controlling atmosphere	Yes	No	No	No
Fire hazard	Great[a]	Small	Small	Small
Possibility of lung collapse, especially under acceleration and deceleration	Great	Small	Small	Small
Middle ear distress during sleep	Possible	No	(No)[b]	(No)
Reduction in vital capacity	Yes	No	(No)	(No)
Eye irritation	Yes	No	(No)	(No)
Substernal pain	Yes	No	(No)	(No)
Cough, nasal congestion, sore throat	Some	No	(No)	(No)
Anemia and paresthesia	Some	No	(No)	(No)
Joint or muscle pain	Some	No	(No)	(No)
Abnormal urinary effects	Some	No	(No)	(No)
Tolerance to ionizing radiation	Small	Good	Better	(Good)
Ease in breathing	Nominal	Nominal	Best	(Nominal)
Possibility of dysbarism after decompression to 3.5 psia				
Bends	No	Possible	No	Unknown
Sluggishness	No	Some	Some	Some
Decompression to 2.3 psia for a few min	Survival	Death	Death	Death
Electrical and electronic equipment	More rugged	Nominal	Nominal	Nominal
Voice pitch	Normal	Normal	Higher	Normal
Weight penalty, lb	Nominal	30	(48)	(3)

[a] Greater toward end of flight and extreme hazard during prelaunch cabin purge at 14.7 psia.
[b] Remarks in parentheses require additional investigation.

position. Even in this most favorable position, a continuous increase of acceleration causes a progressive decrease in arterial oxygen saturation (from 96 to 70%); a delay of approximately 100 sec in this phenomenon was reported by Reed.[63]

Opportunities to study the effects of various environments have been provided by X-15 and Mercury flights. The X-15 pilots use an "open system" helmet with 3.5 psia of pure oxygen against the face. The Mercury capsule used 5.0 psia of pure oxygen without difficulty[88, 89]; similar systems are planned for the Gemini and Apollo.[39, 41] Space stations[20, 55, 81] may use O_2-X_2 at $p_t = 7$ to 10 psia (the latest suggestion is a 50-50 mixture at 7 psia[15, 56]), but the first "Manned Orbital Laboratory" (MOL), scheduled for a 30-day mission in 1968, may use pure oxygen at 5 psia. In the planned American space missions of long duration, at least two crewmen without pressure suits may be located in the space cabin. In the event of a punctured wall or fire, the pressure in the cabin will be reduced to 3.5 psia while the "shirt-sleeve" astronauts don their suits. The cabin pressure will then be reduced even further, if necessary.

In any such specially designed atmosphere, it is important that the astronauts breathe regularly to avoid hypo- or hyperventilation. The former leads to anoxemia, CO_2 retention, and respiratory acidosis. The latter, which is an alveolar over-ventilation at any given metabolic rate, causes a fall in alveolar CO_2 partial pressure and a consequent increase of the CO_2 pressure gradient between tissues, blood, and alveoli. CO_2 is then expired from the lungs faster than it is metabolically produced, leading to "hypocapnia," manifested by dizziness, tingling, impairment of vision, spontaneous tightening of muscles (tetany), and, eventually, loss of consciousness. A slight hypocapnia may also occur when the cabin atmosphere is overpurified of CO_2.[4] For these reasons carbon dioxide sensors have to be supplied in any cabin atmosphere;[11] concentration of CO_2 in excess of 3% in the gas environment is considered harmful.

Table 3 Densities of gases at 7.0 psia and 75°F and at supercritical cryogenic storage

Gas	Mol. wt.	Gas density, lb/ft^3	Critical pressure, psia	Density of supercrit. liq., lb/ft^3
Helium	4.0	0.0048	33	4.3
Neon	20.2	0.0246	380	30.0
Nitrogen	28.0	0.0341	490	19.4
Oxygen	32.0	0.0389	730	26.8
Argon	39.9	0.0485	710	33.0

Decompression sickness (dysbarism) can result from slow, rapid, or explosive decompression. The differentiation between rapid and explosive decompression is disappearing; either implies decompression in less than 1 min. Dysbarism is revealed by bends, embolism, skin manifestations, bone changes, chokes or third-degree bends, staggers, and decompression collapse syndrome (rarely). Altitude acclimatization and denitrogenation of the body by breathing pure oxygen for several hours before launch prevents, or at least reduces, the danger of dysbarism, which is caused by the formation of gas (predominantly nitrogen) bubbles in the blood, body fats, and tissues. According to Henry's law, the amount of an inert gas dissolved in the blood and body fluids at equilibrium will depend on the partial pressure of the gas, the type of fluid, and the temperature. Nitrogen obeys this law, but O_2 and CO_2 do not, because they enter into chemical combinations with hemoglobin and with the buffers of the blood.

At sea level, the partial pressure of nitrogen in air of average humidity is approximately 580 mm Hg. At this partial pressure, 100 cc of blood will dissolve 1.5 to 1.7 cc. When p_{N_2} decreases, the nitrogen comes out of solution. If it comes out slowly, it can be carried from the tissues by the blood and eliminated through the lungs, but if it comes out rapidly, bubbles will form in the tissues, body fats, and blood, to an extent which depends on the degree of supersaturation and the rate of pressure change. Once the bubbles are fully formed, oxygen, carbon dioxide, and water vapor diffuse into them. Nitrogen is five or six times as soluble in fatty tissues as in other body tissues; hence, obese persons are more subject to dysbarism.

Selection of Low-Pressure Atmosphere[87]

Oxygen and various oxygen-inert gas mixtures which might be used for 3-man, 14-day missions are compared in Table 2,[35] and discussed below. Under consideration also is a three-gas atmosphere[92] in which two inert gases are used. One of the inert gases in such a mixture should be nitrogen, which may be biologically necessary, especially during longer missions.[3]

Table 3 shows that the density and critical pressure of an inert gas depends on its molecular weight. The pressure of a supercritically stored gas at cryogenic temperature is only slightly better than the critical pressure. Helium has the lowest critical pressure, but its extremely low temperature requires a fairly thick insulation. Since gas leakage rate is an important characteristic in determining the difficulty of sealing the cabin and the length of time of decompression should a penetration occur,[30] the low molecular weight of He is also a disadvantage. The important criterion for decompression of a "shirt-sleeve" cabin is the time required for the p_{O_2} to reach the minimum allowable value of 2.32 psia. In this respect, the 5.0-psia pure-oxygen atmosphere has the advantage over a 50-50 mixed-gas atmosphere at 7.0 psia. The leakage rate of the former in a three-man cabin may be as high as 0.2 lb/hr—during a 14-day mission, 70 lb may be lost, compared to 47 to 100 lb used metabolically by the astronauts for breathing.

Pure oxygen at 5.0 psia[50]

This system is free of the bends problem, and it is less complicated than a two-gas system, because gas composition does not have to be controlled, except to remove CO_2 created by body processes. It is generally conceded to be a lighter-weight system (a validation study has been made by Michel et al).[47] On the other hand, it presents a fire hazard, which is especially great on the launching pad, when the cabin is purged with oxygen at 14.7 psia; during ascent, the oxygen pressure in the cabin is slowly decreased to 5 psia, decreasing the fire hazard. Even a small fire creates toxic products of combustion[71]; hence, fire prevention measures and/or fire-fighting equipment are mandatory. However, no fire-fighting methods have yet been developed that can cope with a fire in pure oxygen; the best way to extinguish such a fire is by a rapid decompression to 0.2 psia or less, but the donning of a pressure suit takes approximately 5 min. A pure oxygen environment also reduces the life of electronic equipment. Oxidation of organic materials in pure oxygen is enhanced by energetic photons[90] creating trace contaminants.

Oxygen and nitrogen (50-50) at 7.0 psia

Burning rate tests by H. G. Clamann (School of Aerospace Medicine, U. S. Air Force, San Antonio, Tex.; private communication) (Fig. 7) show that this atmosphere is much safer, because accidental fires will be less likely and more readily controlled. Hermann Rahn (University of Buffalo; private communication) has proved that problems of pulmonary atelectasis are greatly reduced by the presence of a second gas in the system. The probability of bends is smaller than in a sea-level atmosphere, due to the lower p_{N_2}, and a pressure change from 7.0 to 3.5 psia is unlikely to cause nitrogen bubbles in the body.[19] The biological role of nitrogen has not yet been resolved, but some may be desirable.[3] The design of electronic equipment and the solution of heat conduction problems are less difficult than in a pure-oxygen environment.

Oxygen and helium (50-50) at 7.0 psia

Of the inert gases other than nitrogen, helium is best understood, because it is used in atmospheres breathed by deep-sea divers and caisson workers. Helium is about half as soluble in water as nitrogen and about one-quarter as soluble in body fats. These low volumetric solubilities prevent bends during decompression. Its low molecular weight leads to rapid diffusion and quick elimination of the gas from the tissues during decompression. Breathing He-O_2 mixtures requires half as much effort as breathing normal air—they have been used to treat asthma and other respiratory diseases. However, helium's density also leads to a greater leak rate, and it causes a pitch increase of the human voice (about one octave), which creates some problems in communication.[68]

Oxygen and neon (50-50) at 7.0 psia

No significant data are available relative to the physiological effects of neon, but it is estimated that its biological effects would lie between those of N_2 and He, coming somewhat closer to the former. The solubility of neon in blood is approximately twice that of nitrogen, but solubility in body fats, which is more pertinent with respect to bends, has not been determined. Neon warrants further exploration, because its relatively low density and high compressibility would lead to a lighter cryogenic storage tank. Thermal conductivity and velocity of sound are very close to those of nitrogen. The other noble gases, argon, krypton, and xenon, are too heavy, and even the lightest of these, argon, is too soluble in body liquids, tissues, and fats (a bends problem); argon also induces a slight narcotic effect.

Pressure Suits

Pressure suits[8, 27, 40] have been used by the X-15 pilots, Vostok cosmonauts, and Mercury astronauts. The design total pressure in the suit is always lower than the cabin pressure, because the suit is used only for emergencies (decompression in the cabin) or for extravehicular purposes (vehicle repair or exploration), in which case it is called a space suit. In the suit used by the X-15 pilots, the suit and the back part of the helmet are cooled with nitrogen from a cryogenic container. Pure oxygen at 3.5 psia enters the front part of the helmet against the face. There is no mixing of oxygen with nitrogen; both gases are continuously vented. The suit used by the Vostok cosmonauts had a 7.5 psia total pressure.[40] For exploring the lunar surface, where the pressure is only 10^{-13} torr (mm Hg), the suit must be of an advanced "semi-closed" type.

Figure 8 shows a space suit and its "back pack," comprised of tanks of oxygen at 900 psia and an evaporative cooler that cools the recirculating oxygen by evaporating the insensible water (picked up by wicks) to space.[27] For relatively long stays, the total pressure should be about 3.7 psia, with $p_{O_2} \geq 3.5$ psia. Man can tolerate such an atmosphere, which corresponds to an altitude of 33,500 ft, for 17 days.[49] Another back-pack design has a Dewar containing liquid air, partially recirculates the air with cool air, and has five main distribution channels (to the helmet and to four extremities). Continuous wearing of a pressure suit requires approximately 1200 cc/day of drinking water, which is more than normal.[86] An extravehicular suit for Gemini, which will enable the astronauts to leave the spacecraft for 45 min, may have the 24-lb

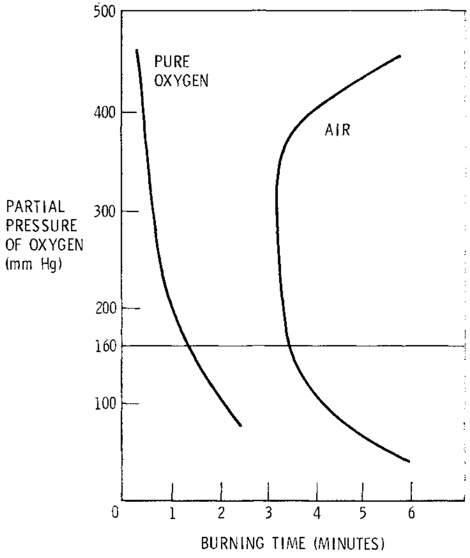

Fig. 7 Typical burning time of combustibles in air and in pure oxygen (Clamann).[22]

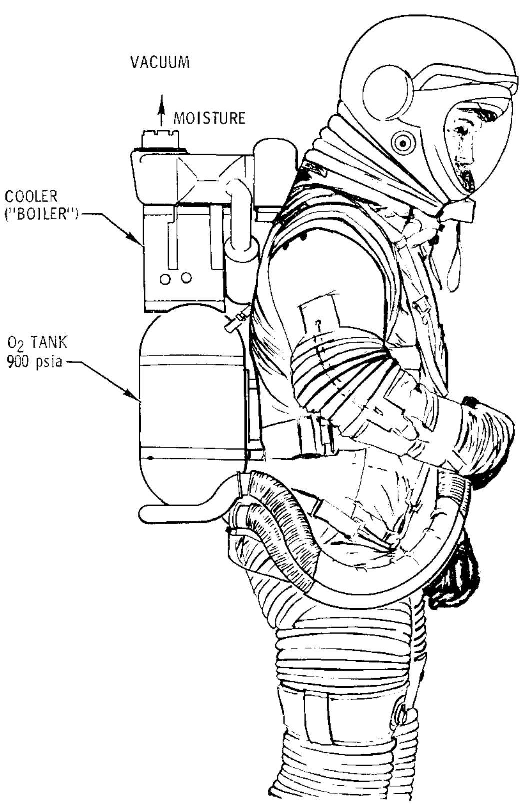

Fig. 8 Extravehicular "moon" pressure suit.

back pack worn either on the abdomen or thigh. In the event of a leak, the unit will be able to maintain oxygen and pressure for 5 min to give the man time to re-enter the spacecraft.

For emergency bailout from high-altitude aircraft (XB-70)[12] and for space vehicles, a "compression tube" or "encapsulation seat" for each man has been proposed.[72] Such devices must be provided with an oxygen system (e.g., chlorate candles that generate oxygen) to sustain the man during re-entry and with a parachute that opens at lower altitudes. Inside these devices the man will be wearing a pressure suit.

Concluding Remarks

The oxygen required for man in a space cabin can be as much as 2.2 lb/day, and leaks can raise this figure to 4 lb/day. Oxygen can be stored at high pressure at room temperature, or stored at cryogenic temperatures, or it may be generated by electrolysis, from chemicals, or by exchange between exhaled CO_2 and chemicals or algae (or higher plants). The algal system, which could fully close the ecological cycle, is the least developed. The presence of ice and/or water-bearing minerals on the moon will permit the generation of oxygen by the electrolysis of water.

The Russian cosmonauts have used air at 14.7 psia in their space flights, and the Americans, pure oxygen at 5 psia. The latter environment is simpler but has a greater fire hazard. It has been proved that man can tolerate such an atmosphere for at least 2 to 4 weeks. However, for longer missions, a two-gas atmosphere at pressures between 7 and 10 psia is advisable. The second gas may be nitrogen, helium, or perhaps neon.

References

[1] Ames, R. K., "Present status of the Sabatier life support system," American Society of Mechanical Engineers, Aviation and Space Conference, Paper no. 63-AHGT-48 (March 1963).

[2] Akerlof, G. C., "Feasibility of regeneration of carbohydrates in a closed circuit respiratory system," J. Spacecraft Rockets **1**, 3, 303–310 (1964).

[3] Allen, S. C., "Role of nitrogen in problem of oxygen toxicity," Physiologist **4**, 2 (August 1961).

[4] Balke, B., "Human tolerances," *Physiology of Man in Space*, edited by J. H. U. Brown (Academic Press, Inc., New York, 1963), pp. 155–164.

[5] Beehler, C. C., Newton, N. L., Culver, J. F., and Tredici, T., "Ocular hyperoxia," Aerospace Med. **34**, 1017–1020 (1963).

[6] Bialecki, A., "Comparative feasibility and logistics of oxygen recovery systems," *Advances in Astronautical Sciences, Bioastronautics* (Plenum Press, Inc., New York, 1963), Vol. 8, Part 3, pp. 164–177.

[7] Bialecki, A., "Submarine air revitalization," ARS Preprint 1223–60 (1960).

[8] Billingsley, J. C. and Le Vora, N., "A self-contained air system and protective suit," Aerospace Med. **34**, 1142–1146 (1963).

[9] Bongers, L. H., "Sustaining life in space—a new approach," Aerospace Med. **35**, 139–144 (1964).

[10] Bovee, H. H. and Schubert, J. E., "Protection against toxic substances in space travel" (abstract only), Aerospace Med. **34**, 1072 (1963).

[11] Bush, W. B., "CO_2 measuring system for manned spacecraft" (abstract only), Aerospace Med. **35**, 261 (1964).

[12] Carter, R. L. and Bagley, W. P., "Emergency egress oxygen requirements," Aerospace Med. **35**, 35–37 (1964).

[13] Casey, R. P. and Lubitz, J. A., "Algae as food for space travel; a review," Food Technol. **17**, no. 11, 48–52, 54–56 (1963).

[14] Casey, R. P., Lubitz, J. A., Benoit, R. J., Weissman, B. J., and Chau, H., "Mass culture of chlorella," Food Technol. **17**, no. 11, 85–89 (1963).

[15] Celentano, J. T., Amorelli, D., and Freeman, G. G., "Establishing a habitability index for space stations and planetary bases," AIAA Preprint 63139 (1963).

[16] Chiles, W. D., Fox, R. E., Rush, J. H., and Stilson, D. W., "Effects of ionized air on decision making and vigilance performance" (abstract only), Aerospace Med. **34**, 773 (1963).

[17] Coe, C. S., "Recovery of oxygen," Chemical Eng. Progr. **60**, 33–35 (1964).

[18] Coe, C. S. and Christensen, G., "Carbon dioxide management in spacecraft atmospheres," Aerospace Med. **35**, 110–115 (1964).

[19] Damato, M. J., Highly, F. M., Hendler, E., and Michel, E. L., "Rapid decompression hazards after prolonged exposure to 50 percent oxygen-50 percent nitrogen atmosphere," Aerospace Med. **34**, 1037–1040 (1963).

[20] David, H. D., "GE test simulates orbiting lab," Missiles Rockets **13**, 31–33 (November 18, 1963).

[21] David, H. M., "NASA, Boeing resuming life-support tests," Missiles Rockets **14**, 28–29 (January 27, 1964).

[22] Del Duca, M. G., Miraldi, F. D., and Babinsky, A. D., "Oxygen regeneration systems for manned space applications," Wright Air Development Div. TR 60-574 (Wright Patterson AFB, Ohio, 1960), pp. 395–440.

[23] Davis, H. and Novosad, R., "Replenishment and stability of life support systems," J. Spacecraft Rockets **1**, 96–103 (1964).

[24] DuBois, A. B., "Oxygen toxicity," Anaesthesiol. **23**, 473–477 (1962).

[25] Ernsting, J., "The ideal relationship between inspired oxygen concentration and cabin altitude," Aerospace Med. **34**, 991–997 (1963).

[26] Eckman, P. K. and Helvey, W. M., "Spacecraft and life systems," Astronaut. Aerospace Eng. **1**, 20–28 (1963).

[27] Fink, D. E., "Hamilton Standard starting manned tests of advanced Apollo suit design prototype," Aviation Week **79**, 48–61 (October 1963).

[28] Gafford, R. D., "Algal photosynthetic gas exchangers," *Proceedings of the Lunar and Planetary Exploration Colloquium* (North American Aviation, Inc., Downey, Calif., November 1963), Vol. 3, pp. 111–117.

[29] Gaucher, T. A., Benoit, A., and Bialecki, A., "Mass propagation of algae for photosynthetic gas exchange," J. Biochem. Microbiol. Technol. Eng. **2**, 339–359 (1960).

[30] Gerathewohl, S. J., *Principles of Bioastronautics* (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963), pp. 425–428.

[31] Gifford, D. and Lucero, D., "A semi-permeable membrane system for carbon dioxide control" (abstract only), Aerospace Med. **35**, 267 (1964).

[32] Helvey, W. M., Albright, G. A., Benjamin, F. B., Peters, J. S., Gall, L., and Rind, H., "Effects on man of prolonged exposure to pure oxygen," 34th Annual Meeting, *Preprints of Scientific Program* (Aerospace Medical Association, St. Paul, Minn., May 1963), pp. 69–71.

[33] Hendel, F. J., "Recovery of water during space missions," ARS J. **32,** 1847–1859 (1962).

[34] Hendel, F. J. "Water recovery from fuel cells and lunar minerals," Ind. Eng. Chem. **56,** 29–31 (1964).

[35] Hendel, F. J., "Gaseous environment during manned space missions," 5th International Symposium on Space Technology and Science, Tokyo (September 1963) (to be published by Japanese Rocket Society in 1964).

[36] Honna, M. and Rinehart, R. W., "Methods of detection and quantification," USN-Lockheed Symposium on Toxicity in Closed Environment, Palo Alto, Calif. (July 1963) (to be published in 1964).

[37] Irvine, L., "Microbiological contamination and its effects in the closed ecological system," USN-Lockheed Symposium on Toxicity in Closed Environment, Palo Alto, Calif. (July 1963) (to be published in 1964).

[38] Jaffe, L. S. and Estes, H. D., "Ozone toxicity hazard in cabins of high altitude aircraft—a review and current program," Aerospace Med. **34,** 633–643 (1963).

[39] Johnson, H. I., "Facilities for manned spacecraft development: simulation and training facilities," Astronaut. Aerospace Eng. **1,** 82–86 (1963).

[40] Konecci, E. B., "Bioastronautics," Astronautics **7** (11), 104–109 (1963).

[40a] Konikoff, J. J., "Regenerative oxygen systems for manned space flights," Wright Air Development Div. TR 60-574, pp. 449–457(1960).

[41] Kuettner, J. P. and Ordway, F. I., "The development of manned space vehicles, I," *Medical and Biological Problems of Space Flight,* edited by G. H. Bourne (Academic Press, Inc., New York, 1963), pp. 1–46.

[42] Lee, W. L. and Donner, W., "Current status of a hypoxia warning system," 34th Annual Meeting, *Preprints of Scientific Program* (Aerospace Medical Association, St. Paul, Minn., May 1963), pp. 85–87.

[43] Leeuwe, H., "On the possible dangers associated with the use of Freon 12 (dichloro-difluoromethane)" (abstract only), Aerospace Med. **34,** 1072 (1963).

[44] Lovell, J. and Morris, F., "Development in the state of the art of regenerable solid absorbent CO_2 removal systems," American Society of Mechanical Engineers 63-AHGT-66, Aviation and Space Conference, Los Angeles, Calif. (March 1963).

[45] Mattoni, R. H., "General principles of biological regeneration for lunar base life support," *Proceedings of the Lunar and Planetary Exploration Colloquium* (North American Aviation, Inc., Downey, Calif., November 1963), Vol. 3, pp. 101–109.

[46] Mayo, A. M., Thompson, A. B., and Whisenhunt, G. B., "Design criteria for a manned space laboratory environmental control system," J. Spacecraft Rockets **1,** 296–302 (1964).

[47] Michel, E. L., Smith, G. B., Jr., and Johnston, R. S., "Gaseous environment considerations and evaluation programs leading to spacecraft atmosphere selection," Aerospace Med. **34,** 1119–1121 (1963).

[48] Mohlman, J. W., "Objectives in development of total recycle processes for life support systems," American Institute of Chemical Engineers Preprint 10, Annual Meeting, Pittsburgh, Pa. (May 1964).

[49] Morgan, T. E., Ulvedal, F., Cutler, R. G., and Welch, B. E., "Effects on man of prolonged exposure to oxygen at a total pressure of 190 mm Hg," Aerospace Med. **34,** 589–592 (1963).

[50] Morgan, T. E., Jr., Cutler, R. G., Shaw, E. G., Ulvedal, F., Hargreaves, J. J., Moyer, J. E., McKenzie, R. E., and Welch, B. E., "Physiologic effects of exposure to increased oxygen tension at 5 psia," Aerospace Med. **34,** 720–725 (1963).

[51] Neville, R. J., "Continuous functional testing of oxygen breathing equipment," Aerospace Med. **34,** 1020–1024 (1963).

[52] Neville, R. J., "Electrochemical device for measuring oxygen," Rev. Sci. Instr. **33,** 51 (1962).

[53] *NASA Life Sciences Data Book* (Webb Associates, Office of Manned Space Flight Headquarters, Washington, D. C., 1962), pp. 1–10.

[54] Oswald, W. J. and Golueke, C. G., "Environmental control studies with a closed ecological system," *Proceedings of the Institute of Environmental Sciences* (Institute of Environmental Sciences, Mt. Prospect, Illinois, 1962), pp. 183–191.

[55] Parker, F. A. and Ekberg, D. R., "Selecting the space-station atmosphere," Astronaut. Aerospace Eng. **1,** 47–52 (August 1963).

[56] Parker, F. A. and Ekberg, D. R., "Atmosphere selection for an orbital space station," AIAA Preprint 63148 (May 1963).

[57] Perry, D. M., "Environmental control development and lunar base support modules," *Proceedings of the Lunar and Planetary Exploration Colloquium* (North American Aviation, Inc., Downey, Calif., November 1963), Vol. 3, pp. 119–126.

[58] Petrocelli, A. W. and Kraus, D. L., "The inorganic superoxides," J. Chem. Educ. **40,** 146–149 (March 1963).

[59] Petrocelli, A. W. and Chiarenzelli, R. V., "The inorganic ozonides," J. Chem. Educ. **39,** 557–560 (November 1962).

[60] Polk, R. L., "Subcritical liquid oxygen storage and conversion system for omnigravic operation" (abstract only), Aerospace Med. **34,** 1073 (1963).

[61] Popma, D. C., "Life support for long-duration missions," Astronaut. Aerospace Eng. **1,** 53–56 (August 1963).

[62] Quattrone, P. D., "Trace contaminant removal," USN-Lockheed Symposium on Toxicity in Closed Environment, Palo Alto, Calif. (July 1963) (to be published in 1964).

[63] Reed, J. H., Burgess, B. F., and Sandler, H., "Effects of arterial oxygen saturation of positive pressure breathing during acceleration," Aerospace Med. **35,** 238–243 (1964).

[64] Ruderman, W. and Carr, L., "Regeneration of oxygen from carbon dioxide in closed ecological systems," Wright Air Development Div. TR 60-574, pp. 157–177 (1960).

[65] Roth, E. M., "Selection of space cabin atmospheres, Part I: oxygen toxicity," NASA TN D-2008, Lovelace Foundation, Albuquerque, N. Mex. (August 1963).

[66] Rutz, L. O., "On the carbon dioxide problem for manned post-Apollo space vehicles," American Society of Mechanical Engineers Paper 63-AHGT-86, Aviation and Space Conference, Los Angeles, Calif. (March 1963).

[67] Saiki, H., "Fatal responses of mice under high oxygen environment" and "Biodynamic responses on retinae of animals," 5th International Symposium on Space Technology and Science, Tokyo (September 1963) (to be published by Japanese Rocket Society in 1964).

[68] Sargeant, R. L., "Speech during respiration of a mixture of helium and oxygen," Aerospace Med. **34,** 826–829 (1963).

[69] Saunders, R. A., "Atmospheric contamination in the space cabin" (abstract only), Aerospace Med. **34,** 674 (1963).

[70] Schaefer, K. E., "Definition of environment," ARS Preprint 2599-62 (1962).

[71] Schuberth, E. R., "Logistic support system considerations for a 15-man earth orbiting space laboratory," AIAA Preprint 63144 (May 1963).

[72] Seeler, H. W. "Complete emergency life sustaining system for spacecraft," Aerospace Med. **35,** (1964).

[73] Sexton, R. E., "Space vehicle thermal and atmospheric control research program," American Society of Mechanical Engineers Paper 63-AGGT-68, Aviation and Space Conference, Los Angeles, Calif. (March 1963).

[74] Shearer, R. E., "Conversion of CO_2 to O_2 with use of lithium carbonate," Wright Air Development Div. TR 60-574 (Wright-Patterson AFB, Ohio, 1960), pp. 459–463.

[75] Sisakian, N. M. and Yazdovski, V. I., "Supporting life in space flight," *Man's First Space Flights: Scientific Results of Medical and Biological Studies Made During the Orbital Flights of the Vostok and Vostok-2 Satellite-Space Ships* (Academy of Sciences Publishing House, Moscow, USSR, 1962).

[76] Slager, U. T., *Space Medicine* (Prentice Hall, Inc., Englewood Cliffs, N. J., 1962); see chapters on pressure environment and metabolism.

[77] Solitario, W. A., Bialecki, A., and Laubach, G. E., "An approach to trace contaminant control for a spacecraft atmosphere," American Institute of Chemical Engineers Preprint 6017, National Meeting, Buffalo, N. Y. (May 1963).

[78] Stokinger, H. E., "Validity and hazards of extrapolation of threshold limit values to continuous exposures," USN-Lockheed Symposium on Toxicity in Closed Environment, Palo Alto (July 1963) (to be published in 1964).

[79] Stubbs, R. A., Bryan, A. C., and Leach, W. G., "Physical evaluation of a polarographic pO_2 sensor and its application as a hypoxia warning device," Aerospace Med. **33,** 209 (1962).

[80] Waggoner, J. N., "Man in space—a medical bonanza," *Medical and Biological Problems of Space Flight,* edited by G. H. Bourne (Academic Press, Inc., New York, 1963), pp. 277–283.

[81] Waggoner, J. N., "On the practical utilization of a biological space laboratory for life sciences experiments," AIAA Preprint 63134 (May 1963).

[82] Ward, J. E. and Wells, J. G., "Background to the space-crew holding facility," Astronautics **5,** 32–33 (1962).

[83] Weber, T. B., Dickey, J. E., Jackson, J. W., Register, J. W., and Conkle, J. P., "Monitoring of trace constituents in simulated manned spacecraft," Aerospace Med. **35,** 148–152 (1964).

[84] Weber, T., "Evaluation of gaseous and particulate components in manned space stations," AIAA Preprint 63-258.

[85] Welch, B. E., "Ecological systems," *Physiology of Man in Space,* edited by J. H. U. Brown (Academic Press, Inc., New York, 1963), pp. 310–319.

[86] Welch, B. E., Cutler, R. G., Herlocher, J. E., Hargreaves, J. J., Ulvedal, F., Shaw, E. G., Smith, G. B., McMann, H. J., and Bell, L., "Effects of ventilating air flow on human water requirements," Aerospace Med. **34,** 383–388 (1963).

[87] Welch, B. E., Morgan, T. E., Ulvedal, F., and Henderson, W. W., "Observations in the SAM two-man space cabin simulator," Aerospace Med. **32,** 583, 591, 603, 610 (1961).

[88] White, S. C. and Reed, J. H., Jr., "Habitability in space stations," AIAA Preprint 63138 (May 1963).

[89] White, S. C. and Berry, C. A., "Resume of present knowledge of man's ability to meet the space environment," Aerospace Med. **35,** 43–48 (1964).

[90] Wilks, S. S. "Toxic photo-oxidation products in closed environments," Aerospace Med. **34,** 838–841 (1963).

[91] Wu, L. S. and Yakut, M. M. "Bio-logistics of a 30, 60, and 100-day manned orbital space station based on the metabolic approach," J. Spacecraft Rockets **1,** 204–209 (1964).

[92] Young, D. R., "Some metabolic aspects of extended space flight," Symposium on Exploration of Mars, American Astronautical Society Preprint 16, Denver, Colo. (June 1963).

JULY-AUGUST 1964 J. SPACECRAFT VOL. 1, NO. 4

Thermal Similitude Studies

BILLY P. JONES*
NASA George C. Marshall Space Flight Center, Huntsville, Ala.

One of the initial objectives of work in thermal similitude is to determine modeling laws and techniques which will find application in thermal scaling of spacecraft and in research problems. Modeling laws for space vehicles are derived from the differential equations used in practice for thermal analysis. The necessary and sufficient conditions for complete thermal similarity between model and prototype take the form of 28 ratios that must remain constant. However, all of these ratios are not independent but contain independent sets of six ratios. An example of thermal scaling is given in which one independent set is used. The general results compare favorably with those of some investigators who used other methods. The purposes of full-scale thermal testing are discussed, and the usefulness of thermal scale modeling as a substitute for full-scale testing is questioned. It is suggested that the principles of similarity and scale modeling may find the most fruitful application in special research problems.

Nomenclature

C_j = heat capacity of jth region, kcal/°K
T_j = temperature of jth region, °K
T_k = temperature of kth region, °K
$\dot{T}_j$ = derivative of T_j with respect to time, °K/hr
C_{kj} = Over-all conduction coefficient between regions k and j, kcal/hr-°K
R_{kj} = over-all radiant coefficient for net radiative transfer from region k to j, kcal/hr (°K)
q_j = internal power dissipation, kcal/hr
${}^SA_j$ = projected area of surface j to sun, m^2
A_j = total area of surface j radiating to space, m^2
ϵ_j = infrared emissivity of surface j, dimensionless
α_j = absorptivity of surface j with respect to solar insulation, dimensionless
S = solar constant, 1200 kcal/hr m^2
σ = Stefan-Boltzmann constant, 4.87×10^{-8} kcal/hr m^2, (°K)^4 (β_j, γ_j, δ_j, η_j, θ, ζ_j, ι_j, λ_j, ω, μ_{kj}, ρ_{kj} are constants of proportionality, as indicated in text)
b_j = particular values of T_j at zero time
F_{kj} = classical geometry factor for net radiation exchange based on Lambert's cosine law for diffuse radiation
E_{kj} = factor in over-all radiation coefficient that depends only on emissivities of surfaces for bodies k and j
R_{A_k} = area for radiation coupling term, m^2
l_2, d_1, d_2, h, a, L_1 = particular linear dimensions, m
V_j = volume of section j, m^3
k_j = thermal conductivity of jth region, kcal/hr-m-°K
$(\rho c_p)_j$ = density-specific heat product for jth region (volumetric heat capacity), kcal/m^3 °K
$(\rho c_p)_N$ = volumetric heat capacity normalized to 6061 alloy $(\rho c_p)_{\mathrm{Al}}/(\rho c_p)_j$
k_N = thermal conductivity normalized KEL-F, $k_j/\mathrm{k}_{\mathrm{KEL\text{-}F}}$
ω_2 = solid angle subtended by A_2, as viewed from dA_1
ϕ_1 = angle between normal to dA_1 and line of sight to differential area A_2

Introduction

THE problems of interest in the field of thermal similitude can be separated into two categories: 1) those for which a mathematical model in the form of descriptive differential equations is available, and 2) those for which adequate governing equations are unknown. Most of this paper is devoted to consideration of the former category.

Similarity Based on *n* Simultaneous First-Order Differential Equations

The following set of n differential equations may be used to describe the temperature behavior of n bodies that are at different but uniform temperatures:

$$C_j\dot{T}_j = \sum_{\substack{k=1\\k\neq j}}^{n} C_{kj}(T_k - T_j) + \sum_{\substack{k=1\\k\neq j}}^{n} R_{kj}(T_k{}^4 - T_j{}^4) + q_j + {}^SA_j\alpha_jS - A_j\epsilon_j\sigma T_j{}^4 \qquad j = 1, \ldots, n \quad (1)$$

Received October 23, 1963; revision received March 16, 1964.

* Research Engineer and Mathematician, Research Projects Laboratory. Member AIAA.