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SPACE-CABIN ATMOSPHERES

Emanuel M. Roth
Project Scientist
Lovelace Foundation
for Medical Education and Research

In spite of early philosophical objections to manned space flight, it is evident that man's presence is a valuable asset in assuring success of the scientific exploration of the solar system. The problem now placed in the lap of the scientific community is the assurance that man will be able to utilize his priceless superiority over the machine in this effort.

In the selection of ideal space-cabin atmospheres there has arisen a fascinating interaction between human physiology, the gaseous environment, the machine, and the mission. The systems approach, which has been so useful an aid in the selection of ideal hardware, must be brought to bear once again. I shall attempt to outline the major reasons for uncertainty in the selection of space-cabin atmospheres and the problem of optimizing the man-machine system in this respect.

The manned flights of the United States and Russia have been successfully accomplished with diametrically opposed philosophies regarding cabin environments. The Russians have chosen for their flights an oxygen-nitrogen environment of essentially the same composition and pressure as air at sea level. With less of a weight problem than the United States has had, their philosophy has been "Better the devil you know than the one you don't." In Project Mercury, simplicity of control engineering and minimization of weight were considerations which led to selection of 100 percent oxygen at 5 psi as the cabin atmosphere. Current plans for Gemini are to repeat the successful 100 percent oxygen of Project Mercury. These plans extend to the 14-day Apollo program, but with much less certainty than in the past. The use of 50 percent oxygen in nitrogen at 390 mm Hg (7 psi) or ½ atmosphere has been seriously considered and is still being studied as a possible choice.

These represent only three of the many possible gaseous environments. Unfortunately, the pressure of engineering commitments involved in the development of spacecraft requires that decisions be made early, often before the physiological tolerance to unnatural gaseous environments can be determined. In the past, selection has been primarily on engineering grounds, with the burden of proof on the physiologist that such environments cannot be tolerated. While this approach has been adequate for previous flights, it has serious drawbacks for the longer and more hazardous missions of the future. The cost and complexity of physiological studies of exotic gaseous environments appear justified not only by these mission considerations but by the light which they can shed on the problems of respiratory physiology and pathology which still plague us on Earth.

The variables of the cabin environment which must be considered are:

1. Total pressure
2. Oxygen pressure
3. Carbon dioxide pressure
4. Inert-gas pressure
5. Water-vapor pressure
6. Gaseous trace contaminants
7. Thermal properties of gas
8. Circulation of gas
9. Temperature of gas
10. Leakage rate of gas
11. Duration of exposure
12. Gravitation level

There are also numerous physiological and pathological variables on which these environmental variables may act:

1. Alertness and performance
2. Communication

3. Time of useful function
4. Decompression syndromes
    - (a) Aeroembolism and bends
    - (b) Barootitis and barosinusitis
    - (c) Cardiovascular collapse
5. Respiratory physiology
    - (a) Atelectasis
    - (b) Hypoxia
    - (c) Hypo- and hyper-capnia
    - (d) Hemoglobin control
6. Oxygen toxicity syndrome
7. Radiation sensitivity
8. Fire and blast hazards
    - (a) Meteoroid-penetration effects
    - (b) Cabin-fire control
9. Bacterial flora changes and infections
10. Water physiology
11. Thermal-control problems

Lack of information beclouds the interaction between the environmental and physiological variables over long periods of time. Let us see what happened to some of the simpler environmental variables in previous space flights. Ideally, the temperature in a cabin should be 60° to 80° F and humidity 40 to 70 percent. In the early Mercury flights, trouble with the temperature-control system caused excessively high temperatures during early phases of the mission. The humidity-control system also had its difficulties. These arose primarily through action of another variable—gravity. In zero gravity, the control of waterflow becomes quite tricky and devices for adequate humidity control require ingenious engineering. The rather moist state of most of the Mercury astronauts testifies to the difficulties of water control that may arise in experimental programs. Future zero-gravity technology may be expected to improve these systems. A complicating factor is the tendency to integrate systems. The integration steps bring up new potential problems which, as always, appear at most embarrassing times in an otherwise successful system.

Now, what about carbon dioxide? Studies of carbon dioxide hazards in nuclear submarines have led to the concept that for prolonged periods of time this gas should be kept below 0.5 percent in the atmosphere. In the Mercury program, this control was successful. However, as flight durations are prolonged and simple chemical absorption systems are replaced with complicated devices which can regenerate oxygen from carbon dioxide, the danger of malfunction rears its ugly head.

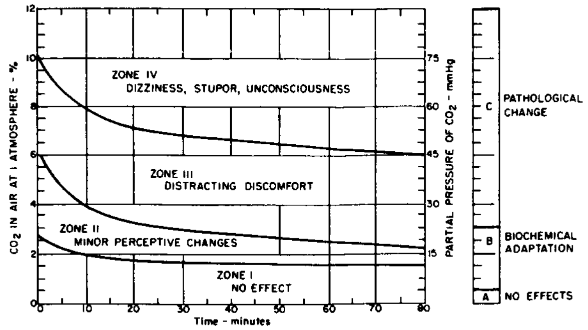

FIGURE 1.—Effects of carbon dioxide on man.

Figure 1 illustrates some of the problems which carbon dioxide alone will give us. At high concentrations, exposure for short periods of time causes dizziness, stupor, and unconsciousness. These exposures may arise in a fire situation as a result of either fire or fire extinguishers. At lower levels, after longer periods of time, carbon dioxide can cause distracting discomfort which may interfere with a mission. At very low levels, biochemical changes occur which, though not a danger *per se,* may well combine with other stresses to get the astronaut into difficulty. This is especially true in the case of oxygen poisoning.

The selection of total pressure within a space cabin has been determined by engineering considerations. In past designs it was felt that cabin pressure had to be kept below 5 lb/sq in. or about 1/3 atmosphere to avoid the excessive weight of cabin wall required to maintain higher pressures. Recent studies have shown that an increase in the pressure to 7 lb/sq in. can be handled with a weight increase of only 8 pounds. As technology improves, one may find that cabins of 1 atmosphere are compatible with the weight requirements of the overall mission. Filament-wound fiber glass plastics are being considered as a weight-saving device. These create other problems which remain to be solved, such as the effects of hard vacuums on the plastic fillers between fibers and the effect of meteorite penetration.

For every total pressure in a sealed cabin there is an optimum percentage of oxygen and a range above and below which there is danger. Figure 2 summarizes most of what is known about this relationship. In order to keep the oxygen pressure in the lungs equivalent to sea level, one must increase the oxygen percentage as the pressure is reduced. The sea-level-equivalent line is presented on the graph. Thus, at 24,000 feet, over 60 percent oxygen is re-

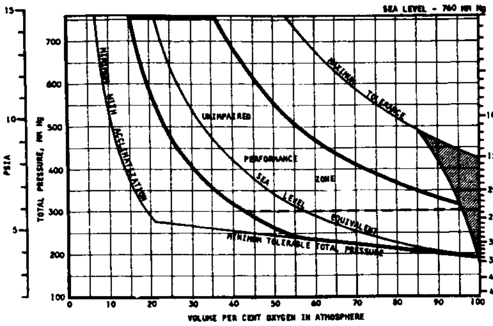

FIGURE 2.—Oxygen-pressure effects. (After Luft.)

quired. At 33,000 feet, 100 percent oxygen is required. The body can tolerate oxygen levels in the lungs lower than sea level without impairment. The lower heavy curve in figure 2 represents the lower limit of unimpaired function. Any cabin or suit system must be kept above this line.

What about excessive oxygen or the problem of oxygen poisoning? Unfortunately, man has not been designed to tolerate excess oxygen. Deep-sea fish are the only creatures that face, in nature, the problem of excess oxygen. Through the ages, even sea-level animals have recurrently faced the problem of oxygen deficiency for short periods of time and have developed elaborate devices to compensate for this unhappy state. With no exposure to excess oxygen pressure to direct the evolution of physiological devices, land animals have developed none. The upper heavy curve in figure 2 represents the onset of oxygen toxicity. At sea level, over 40 percent oxygen for long periods of time leads to pathological changes in the lungs. Oxygen tents in hospitals leak in enough air to keep patients out of danger from oxygen toxicity. As the pressure within a sealed cabin is reduced, the percentage of oxygen can be increased without danger to the crew. This is fine for space cabins where the lowest possible pressure is best from an engineering point of view. Fine, except for one point. As we approach 100 percent oxygen, the general rules of the game appear to change. Results of recent studies of 14 days' duration have suggested that there is a possible danger after exposure to pressures of oxygen slightly above the sea-level oxygen pressure. This is most unfortunate, since engineers would appreciate the simplicity of controlling only one gas.

It is true that Astronaut Cooper was exposed to such pressures for 34 hours without obvious ill effects. However, both animal and human experiments suggest that he just slipped under the wire.

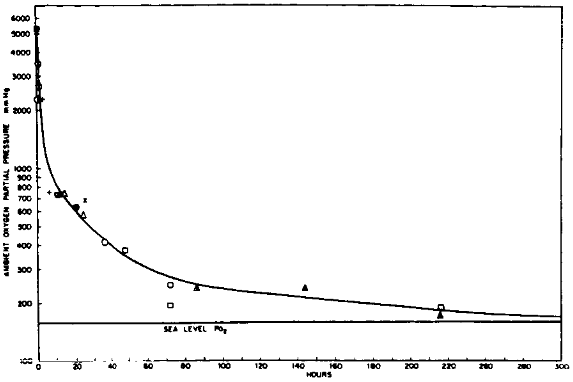

FIGURE 3.—The time factor in oxygen toxicity. (After B. E. Welch.)

Figure 3 is a review made by Dr. Welch at the U.S. Air Force School of Aerospace Medicine, Brooks Air Force Base, of the time factor in oxygen toxicity. All points above the curve represent symptoms of oxygen poisoning. The experimental points represent time of onset of first symptoms. Deep-sea divers get into trouble with oxygen pressures in the 2,000 to 6,000 mm Hg range. They suffer nausea, dizziness, convulsions, and loss of consciousness within several minutes to hours. Humans exposed to 80 or 90 percent oxygen at sea level have no nervous symptoms but suffer coughing and pneumonia after about 1 day's exposure. The exposure of Astronaut Cooper fell at the 250 mm Hg, 34-hour point, just below the line.

Recent experiments at several laboratories have shown a variety of late symptoms occurring below ½ atmosphere of pure oxygen. The most common symptom is earache caused by the absorption of oxygen from the middle ear during sleep. This is similar to ear discomfort from change in altitude. Chest pain has been reported, as has decreased breathing capacity on maximum effort. These symptoms have been attributed to collapse of lung segments or atelectasis. The inert gas, nitrogen, ordinarily acts as a brake to prevent collapse of the lungs. When one breathes 100 percent oxygen, the rapid uptake of this gas by the blood often empties the alveoli or air sacs and collapses the lung segments. Of greater concern have been isolated cases of paralysis and liver damage in animals under these conditions. These may have been due to the triggering of virus infections by the slight elevation in oxygen tension. Human subjects have come down with severe anemias and kidney damage after 60 to 80 hours.

What is not clear is the role of nitrogen in the physiological processes and the role of trace contaminants in the sealed cabins which can react or combine with the unusual oxygen environment to produce undefined toxic agents. In any event, the use of 100 percent oxygen environments is not without danger. Recent studies in the space-cabin simulator at the U.S. Air Force School of Aerospace Medicine, using 100 percent oxygen at 5 psi for 30 days, have resulted in no symptoms. This would suggest that the 14-day Apollo mission may be safe under such conditions, providing the cabin does not produce unusual chemical agents which may, even in trace amounts, combine with oxygen to give unexpected trouble. It will take full simulation in the Apollo vehicle for up to 30 days to eliminate cryptic toxic hazards.

Because carbon dioxide can dilate blood vessels in the brain and lungs, this gas increases the danger of any given pressure of oxygen. Another interesting synergism is the additive effect of oxygen and radiation. Both oxygen and radiation appear to destroy cells by a common mechanism. They both generate free radicals or very active compounds which destroy critical structures. Thus, the solar and cosmic radiation hazards in space missions intensify oxygen problems and vice versa. Much work is still required to define the synergism.

The problem of oxygen toxicity in space has very definite parallels in clinical medicine. In recent years clinicians have used sealed chambers with several atmospheres of oxygen to increase the oxygen content of the blood in such disorders as tetanus, carbon monoxide poisoning, strokes, myocardial infarcts, and many other disorders where critical pathology is a matter of local oxygen defect. This approach to hypoxic states recently came to the public interest when it was used, though unsuccessfully, on the child of our late President. Understanding of the subtle cellular changes in space-cabin environments will go a long way in defining the changes brought about by this new therapeutic device.

The synergism between oxygen and radiation also has clinical implications. The sensitivity of internal tissues to radiation can be modified by placing patients in high-oxygen environments. It thus may be possible to increase the effective internal X-ray dose without increasing the skin dose. Since damage to the skin often limits a radiologist's approach to cancer therapy, it is quite important that the subtleties of the "oxygen effect" be adequately studied. Here again, the basic problems of space medicine and clinical medicine run parallel paths. Both should benefit from research directed against common problems.

Other changes may well occur with elevation of oxygen pressures. Bacterial flora on the skin and in the mouths of subjects exposed to unusual oxygen environments do change. Many of the anaerobic bacteria are killed and thus the ecology of these surface organs is changed. So far, no symptoms have arisen in experimental subjects, but one must consider the long-range effect on such phenomena as dental caries and gum disorders. Once again, these studies should shed light on the natural ecological balances of the body surfaces in earthy environments.

What about the fire hazard? We all know that combustibles burn at much greater rates in oxygen. Is this a tolerable hazard in space vehicles? A recent review by the Lovelace Foundation has shed some light on the fire and blast hazard in space cabins. The effects of inert gases in the combustion process have been studied in the past for the prime purpose of developing equations which define the combustion process for engine applications. In space cabins this role of inert gases has very direct and practical implications to the designer.

In recent years there have been two relatively serious fires in cabin simulators using 100 percent oxygen. Analysis of these fires suggests that there remains much work to be done in the selection of fabrics, plastics, and combustible liquids of all types for high-oxygen environments. This selection process will have

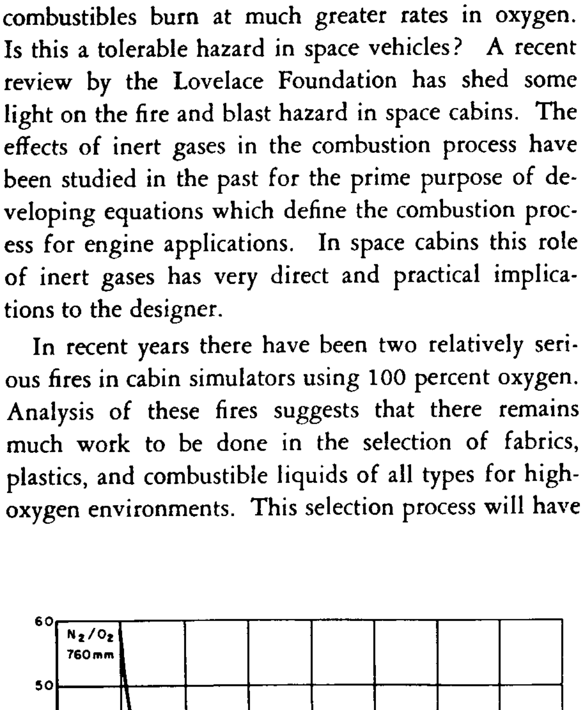

FIGURE 4.—Effect of oxygen pressure on burning time. (Modified from Parker and Ekberg.)

much carryover in the design of high-pressure chambers for therapeutic purposes. Fortunately, there have been no therapy-chamber accidents, but the hazard still looms large.

Can the fire danger of 100 percent oxygen environments be tolerated in space cabins? What are some of the numbers involved? Figure 4 indicates that the rate of burning in the 100 percent oxygen atmosphere of the Mercury cabin is almost 3 times the rate in air at sea level. The ignition energies required for gases can be several orders of magnitude greater in 100 percent oxygen than in air. Conversion of flame to detonation is aided by increasing oxygen. Fireproofing agents effective at sea level are no longer effective with elevation of oxygen to even as little as 40 percent. Most of the fireproofing data stem from studies by the British welding industry. New methods of welding involving exotic materials and techniques will benefit from studies of fireproofing in space-cabin atmospheres.

A fascinating study is the relative effect of different inert gases on the overall fire hazard. Is any one gas overwhelmingly better than the others in the space cabin? Unfortunately, theories of the physical chemistry of the combustion process predict that each burning parameter will be affected differently. The confusion is pointed out by table I, which shows that each factor has its own optimum gas. Consensus by the combustion community favors nitrogen, but this is based more on intuition than cold fact. A missing link in the whole picture is the role of zero gravity. Absence of convection does reduce the burning process, but the degree of safety to be afforded by this state is yet to be determined. Lack of convection, however, increases the tendency to form hot spots and aggravates ignition problems. Absence of gravity also modifies fire-extinguishing techniques in that the dense vapors used on Earth lose their blanketing effect. Extinguishing vapors in a cabin present severe toxic hazards which are currently under evaluation. The basic concepts of fire prevention and extinguishment on Earth will be greatly expanded by the need to understand the space-cabin problem.

TABLE I.—*Summary of Effects of Inert Gases on Flame Propagation (after C. E. Mellish and J. W. Linnett, "The Influence of Inert Gases on Some Flame Phenomena," in Fourth Symposium (International) on Combustion, The William & Wilkins Co., Baltimore, 1953)*

In reducing burning velocities	$CO_2 > N_2 > A > He$
In decreasing composition range for flammability:	
Wide tubes	$CO_2 > N_2 > He > A$
2.2 cm diam	$CO_2 > He > N_2 > A$
1.6 cm diam	$He > CO_2 > N_2 > A$
In increasing minimum spark-ignition pressure:	
$(H_2 + O_2)$, low pressure	$He > A > N_2 > CO_2$
$(H_2 + O_2)$, high pressure	$CO_2 > N_2 > A$
$(H_2 + N_2O)$, low pressure	$He > CO_2 > N_2 > A$
In increasing minimum spark-ignition energy:	
$(H_2 + O_2)$, atm. pressure	$He > CO_2 > N_2 > A$
$(CH_4 + O_2)$, atm. pressure	$He > N_2 > A$
In increasing quenching distance:	
$(H_2 + O_2)$	$CO_2 > He > N_2 > A$
$(CH_4 + O_2)$	$He > N_2 > A$

The possibility of meteoroid penetration must also be considered. The injection of liquid metal into a cabin by a penetrating meteoroid presents a serious blast and flash problem within the cabin. The danger of lung blast is probably minimal for particles with energy great enough to just penetrate the wall of the cabin. Larger particles could cause lung damage, but these are quite rare. The flash of molten vapor in 100 percent oxygen is similar to the flashbulb effect and can produce blindness lasting as long as several minutes. From recent calculations it appears that permanent retinal blindness, as seen after nuclear flashes, will not be a problem. Ignition of combustibles such as fabrics and plastics by hot vapor is a potential hazard. Fortunately, the chances of penetration of current space vehicles by meteoroids has recently been shown to be several thousand times lower than estimated 5 years ago. Figure 5 summarizes current predictions. Except for travel in the asteroid belt, it would appear that the meteoroid problem would rank quite low as a criterion in selection of space-cabin atmospheres. The basic problem, however, is of great interest to many disciplines and is under continuing investigation.

After considering all the above arguments, is the concern about fire and blast risk resulting from 100 percent oxygen environments only academic? At first sight, the arguments presented do seemingly reduce the concern. It is easy to say that sophisticated safety design will eliminate ignition and fuel sources and that training will eliminate human error. It is also easy to rely on the dumping of cabin pressure, zero-

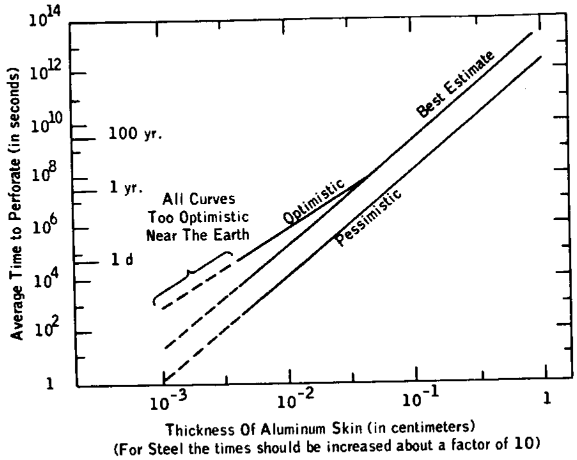

FIGURE 5.—Meteoroid perforation of thin metal skin. in space. (After F. L. Whipple, "On Meteoroids and Penetration," presented at the Interplanetary Missions Conference, American Astronautical Soc., Jan. 1963.)

gravity fire attenuation, and detector-extinguisher systems as backup for potential design failures. It is difficult, however, to assign to many of these factors a probability of success or failure. The ultimate question, of course, is this: Is the increase in overall probability of mission failure brought about by the fire risk of 100 percent oxygen environments greater than the overall probability of failure brought about by the added weight and complexity of a multigas cabin system? The fire risk of 100 percent oxygen is one aspect of the problem. The risk of oxygen toxicity, already discussed, is another. The two must be added together to assess the overall risk of 100 percent oxygen environments.

The general engineering approach must take into account all probabilities of the fire risk. Figure 6 indicates a simplified scheme of how a computer program can approach the problem. Such studies are currently being attempted, but the number of unknowns in the space-cabin environments makes such an approach seem quite naive. More data on the physical processes involved will help validate the method. In conclusion, it cannot be stated with certainty on the basis of present data that, as regards fire hazard alone, 100 percent oxygen should be eliminated as an atmospheric environment in space cabins. The closer to the 8,000-foot air atmosphere of the present-day commercial airliner, the safer the choice. Any compromise of this "ideal" should be in favor of more inert diluent and lower total pressure. Also, the more closely the ideal fire-prevention design and the ideal detection and extinguishing systems are approximated, the less significant becomes the choice of atmosphere. Simulation of the burning hazards in unmanned orbiting vehicles is expensive, but may in the last analysis be the most fruitful source of information for design decisions.

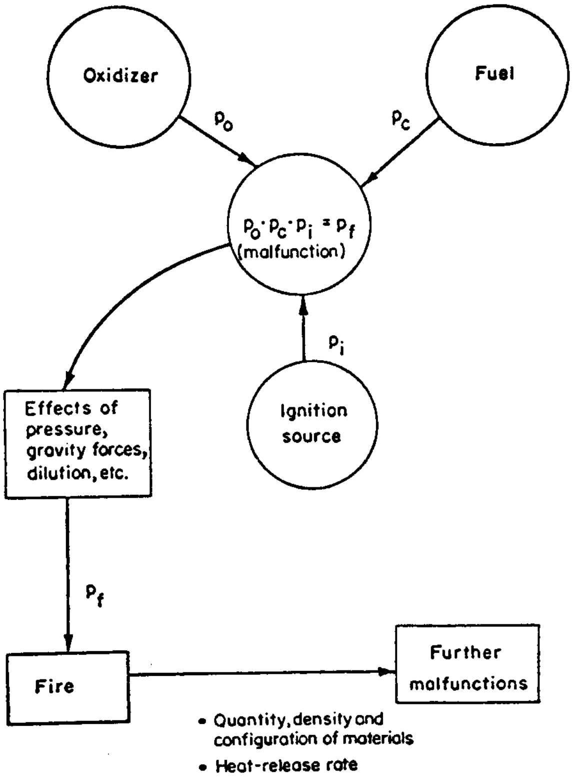

FIGURE 6.—The fire situation. (After H. Cary et al., "A Study of Reliability of Flight-Vehicle Fire-Protective Equipment," ASD TR 61–65, Battelle Memorial Inst., 1961; ASTIA No. AD–268574.)

Lastly, why should we worry about the presence of inert gases in the space cabin? The major factor appears to be the decompression problem. For many decades divers and aviators have been exposed to this hazard. Sudden reduction of pressure releases the dissolved gases in the bloodstream and tissues to form bubbles. These bubbles cause severe joint pains called "the bends," and often give more serious trouble in the form of cardiovascular and nervous-system collapse. Penetration of space vehicles by meteoroids or by accidents of varied types requires that the crew protect themselves against decompression. Unfortunately, space suits provide pressure equivalents of 30,000 to 40,000 feet, pressures low enough to cause bends. If the crewman must get about and exercise vigorously to repair the damage, his susceptibility to bends increases.

Nitrogen, unfortunately, is very soluble in the fats of the body and can form these bubbles quite readily. It can be shown that after decompression this gas would be more hazardous than helium or neon, though less hazardous than argon, krypton, or xenon. Unfortunately, we know man can exist indefinitely in nitrogen; we are not sure about helium; and we are completely in the dark about neon. Actually, until recent months there has been absolutely no biological data on neon. Helium does have some queer metabolic effects on lower animals, but it seems to be tolerated by monkeys for periods as long as 14 days at 7 atmospheres pressure. The U.S. Navy has started similar studies on man. Helium has been shown to be more favorable than nitrogen in regard to bends after prolonged underwater exposure. There is reason to believe that helium will be more favorable than nitrogen after space decompressions. Neon should, theoretically, be more favorable than nitrogen but less favorable than helium. However, since neon is more efficiently stored in cryogenic form and offers less leak wastage than does helium, it remains a serious candidate for space cabins.

For cabins with 50 percent oxygen in nitrogen at ½ atmosphere, a seriously considered alternate in the Apollo project, decompression should not be a danger. Recent studies have shown that this environment, even after prolonged exposure, reduces the dissolved nitrogen enough to minimize bends complications in space suits. In the less likely cabins with 1 atmosphere pressure, helium or neon appears to be a better candidate. Interestingly enough, "the devil we don't know"—100 percent oxygen—is the most favorable gas in decompression events. We are today quite ignorant of the role of inert gases in physiological processes. We have evolved in a nitrogen environment and have adapted to it biochemically. There have been recent reports that suggest that nitrogen is needed in the atmosphere for embryological development, but subsequent attempts to repeat these experiments have led to equivocal results. Clinically, the role of inert gases has much theoretical significance. Many of the anesthetic agents are as "biochemically inert" as the noble gases, but have profound physiological effects. The specific mechanism of action of these agents is still unknown. Since nitrogen at high pressure and krypton and xenon at sea level can be anesthetic agents, it would appear that these gases present excellent model systems for studying anesthesia. The space program has already stimulated several projects along this line, and more appear to be springing up every day. Our long neglect of this fascinating area has finally come to an end.

Thus, we see that choosing a space-cabin atmosphere represents a rather complex decision. It must be tailored to the vehicle, to the mission, and to the state of knowledge regarding many physical and biochemical variables. The more complex space-station and interplanetary missions will no doubt add to the confusion. However, as in most scientific areas, the period of confusion leads to one of more complete understanding, simplification, and utilization. The hurried confusion of space science is no exception.