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CHAPTER 5
ENVIRONMENTAL FACTORS

by

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Introduction

Although many gaseous environments could have been used for the Apollo spacecraft, technological constraints existing in the early manned space flight program dictated the selection of the atmosphere ultimately used. Ideally, from a physiological point of view, the optimum spacecraft atmosphere would have simulated normal or near-normal sea level conditions. Because the state-of-the-art was not sufficiently advanced to cope with the weight and volume penalty imposed by maintaining such an atmosphere, and since spacecraft decompressions could not be precluded, compromises had to be made which resulted in the choice of a spacecraft atmosphere that was not optimum from all points of view, but which was adequate based on practical considerations and the results of appropriate validation tests (Michel et al., 1963).

In addition to establishing the acceptable range of atmospheric composition and pressure, consideration had to be given to the establishment of acceptable carbon dioxide levels, to thermal comfort criteria, and to acceleration and impact limits.

Atmosphere Selection Considerations

The prime design requirements in any spacecraft system are minimum weight, volume, and power usage; reliability, ease of maintenance, environmental compatibility, integration with other systems, and crew compatibility. In Project Mercury, a 100 percent oxygen, 34 500 N/m^2 (5 psia) spacecraft atmosphere was selected. Although such physiological considerations as maintenance of adequate oxygen partial pressure and protection against decompression sickness were examined, the decision to use this atmosphere was based primarily on the engineering considerations described above and the fact that the longest Mercury mission was 34 hours in duration.

Atmospheric Pressure and Composition

During initial planning for the Apollo Program, biomedical experts of the NASA Space Task Group recommended a spacecraft atmosphere composed of 50 percent oxygen and 50 percent nitrogen, at a pressure of 48 300 N/m^2 (7 psia). This recommendation was approved, and contracts were awarded for the development of a suitable environmental control system (ECS). Research involving mixed gas atmospheres was initiated and mainly directed toward assessment of the potential dysbarism hazard following either planned operational or emergency decompressions to the space suit oxygen atmosphere of 25 500 N/m^2 (3.7 psia) (Damato et al., 1963).

Before the completion of Project Mercury, the decision was made to implement the Gemini Program which would bridge the gap between Project Mercury and the Apollo Program. The plan was one of minimum change and essentially involved enlarging the Mercury spacecraft to permit occupancy by two crewmembers. The mission of the Gemini Program was to obtain data and operational experience required for the Apollo Program. From an engineering aspect, it was desirable to continue using the 34 500 N/m^2 (5 psia), 100 percent oxygen atmosphere, provided that this atmosphere was physiologically adequate for periods of as long as 14 days.

Several questions arose concerning the physiological acceptability of the pure oxygen atmosphere for extended durations. At this time, the potential toxicity of oxygen at 34 400 N/m^2 (5 psia) had not been resolved. Additionally, it was felt that an inert gas should be included in any artificial atmosphere as protection against atelectasis. Accordingly, a comprehensive validation program was instituted by NASA in cooperation with the National Academy of Sciences Working Group on Gaseous Environments. Both industrial and Department of Defense laboratories were used in the program. Data obtained from these studies indicated that exposure of man for 14 days to the 100 percent oxygen, 34 500 N/m^2 (5 psia) atmosphere selected for the Gemini spacecraft would not impose any physiological problem (Morgan et al., 1965; Welch et al., 1965; Helvey et al., 1965; Mammen et al., 1965). As a result of these findings, the Apollo Program Office elected to use this atmosphere in the Apollo spacecraft.

Subsequent atmosphere validation tests up to thirty days in duration indicated that the 100 percent oxygen, 34 500 N/m^2 (5 psia) atmosphere was physiologically adequate (Herlocher, 1964; Robertson et al., 1964; Zalusky, et al., 1964). These studies clearly indicated, however, that this atmosphere was associated with nuisance findings such as aural atelectasis, eye irritation, and nasal congestion. Medical investigations associated with Gemini manned space flights resulted in suggestive, but not conclusive, evidence of hematologic changes resulting from exposure to a single gas atmosphere (Fischer et al., 1967). A consistent, time-related decrease in red cell mass was observed (Richardson et al., 1972). Although the causes and implications of this decrease in red cell mass were not completely understood they were not considered to be a deterrent to the use of 100 percent oxygen at 34 500 N/m^2 (5 psia) for Apollo spacecraft because of the limited duration of these missions.

Apollo preflight checkout procedures initially encompassed an overpressurization of the Command Module (CM) using 100 percent oxygen. After the Apollo fire, these procedures were modified, and a mixture of 60 percent oxygen and 40 percent nitrogen was used to reduce the fire hazard. The CM was launched with this gas composition, which eventually was built up to almost 100 percent oxygen, through leakage makeup with oxygen, in a time frame shown in figure 1. Additional decompression studies were performed to determine whether any dysbarism problems existed under these conditions (Maio et al., 1969; Maio et al., 1970; Allen et al., 1971). The results of these studies showed that potential dysbarism problems were minimal.

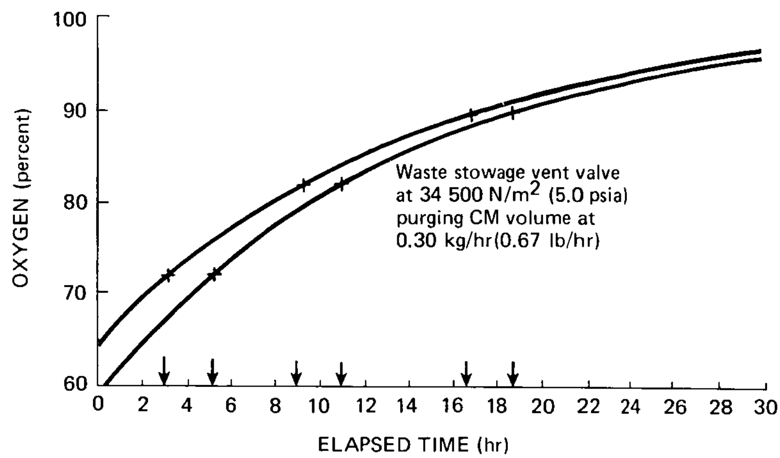

Figure 1. Command Module oxygen purge after launch.

The atmospheric pressure and composition after each launch remained between 32 406 and 35 164 N/m^2 (4.7 and 5.1 psia) at almost 100 percent oxygen for the duration of each mission, including the time in the Lunar Module (LM). During extravehicular activity (EVA), the suits were pressurized to 26 546 $\pm$ 1034 N/m^2 (3.85 $\pm$ 0.15 psia) with 100 percent oxygen. No untoward atmospheric effects, such as hypoxia, dysbarism, or oxygen toxicity, were experienced during any of the Apollo missions.

Carbon Dioxide Concentration

Because carbon dioxide has a powerful stimulatory effect on respiration as well as a marked influence on acid-base balance, the problems of carbon dioxide removal and the ability of man to perform adequately when exposed to various concentrations of carbon dioxide have become important. Synergistic interactions were considered independently in establishing acceptable levels of carbon dioxide for the Apollo Program. The optimal mission design level was established as 505.4 N/m^2 (3.8 torr) carbon dioxide partial pressure, with a maximum limit for continuous exposure of 1010.8 N/m^2 (7.6 torr). The emergency limit was set at 1995 N/m^2 (15.0 torr) carbon dioxide partial pressure.

The carbon dioxide levels recorded by sensors in the Command and Lunar Modules remained well below the limit of 1010.8 N/m^2 (7.6 torr) except for the return flight of the Apollo 13 spacecraft. The Lunar Module environmental control system was used for approximately 83 hours on this mission, and the first lithium hydroxide cartridge was used for approximately 83 man-hours. During this time, the carbon dioxide level was permitted to increase to an indicated 1981.7 N/m^2 (14.9 torr). Subsequently, four CM cartridges were used in a special arrangement devised and tested at the Lyndon B. Johnson Space Center during the mission. By using this arrangement of four lithium hydroxide cartridges, carbon dioxide levels were maintained between 13.3 and 239.4 N/m^2 (0.1 and 1.8 torr).

Space suit carbon dioxide levels were maintained within nominal limits by proper control of oxygen ventilation flow as predetermined by laboratory testing (Michel et al., 1969). The constant flow rate used was 0.15 m^3/min (5.5 ft^3/min).

Thermal Comfort

The space environment has no known effect on the thermoregulatory center, and there is no evidence that any effect might exist. However, it must be ensured that these environments do not exceed known limits within which thermoregulation can be maintained.

No major problems in thermoregulation were experienced during Project Mercury or the Gemini and Apollo Programs. However, thermal stress may have contributed to the shortening of some Gemini extravehicular activity. More extensive EVA and larger vehicles that permit more activity are conditions that will complicate the heat removal system design for future missions.

The design range for temperature and humidity control in the Apollo Command Module was 294° to 300°K (70° to 80°F) with a relative humidity of 40 to 70 percent. Similarly, the design range for the Lunar Module was 291° to 300°K (65° to 80°F) with a relative humidity of 40 to 70 percent. Thermal comfort and tolerance criteria were developed during the Apollo Program. Although these criteria did not replace the Apollo specifications, they were used frequently to assess the adequacy of pressure suit temperature control and in some instances to evaluate the acceptability of contingency cabin environments (Waligora, 1970). These criteria predicted a slightly cooler and expanded comfort range for the Apollo spacecraft environment compared to the 101 356 N/m^2 (14.7 psia) Earth environment.

Temperature in the CM was controlled through a combination of coldplate wall radiators and a cabin-gas heat exchanger. In practice, however, the gas heat exchanger was neither effective nor necessary and because it increased the ambient noise level it was seldom used. The ambient temperature sensor was located near the inlet to the heat exchanger and it was necessary that the heat exchanger be operating to provide a representative ambient temperature reading. Typically, when the heat exchanger was turned on the temperature reading immediately rose 2.2° to 3.3°K (4° to 6°F), although no constant offset can be assumed. The data from this sensor are presented in table 1.

No operational humidity measurements were made. Relative humidity was measured with a portable device on the Apollo 7 spacecraft and was found to be within the design range of 40 to 70 percent.

Table 1
Command Module Cabin Temperatures in °K (°F)
Measured at the Inlet to the Heat Exchanger (See Text)

Apollo Flight	Inflight			
	Launch	Average	Range	Reentry
7	294.3 (70)	294.3 (70)	290.9 to 299.3 (64 to 79)	291.5 (65)
8	291.5 (65)	295.4 (72)	289.3 to 300.4 (61 to 81)	289.3 (61)
9	291.5 (65)	294.3 (70)	291.5 to 295.4 (65 to 72)	292.6 (67)
10	297.0 (75)	295.9 (73)	290.9 to 299.8 (64 to 80)	287.6 (58)
11	294.3 (70)	290.4 (63)	285.9 to 295.9 (55 to 73)	285.9 (55)
12	294.3 (70)	292.6 (67)	287.6 to 299.8 (58 to 80)	288.7 (60)
13	294.3 (70)	290.9 (64)	287.6 to 294.8 (58 to 71)	297.0 (75)
14	294.3 (70)	296.5 (74)	288.7 to 298.2 (60 to 77)	288.1 (59)
15	294.3 (70)	293.7 (69)	288.1 to 300.4 (59 to 81)	288.1 (59)
16	294.3 (70)	294.3 (70)	287.0 to 299.8 (57 to 80)	287.0 (57)
17	294.3 (70)	293.7 (69)	289.3 to 300.4 (61 to 81)	289.8 (62)

Crew comments indicated that the Command Module was uncomfortably cool during several missions, especially during sleep periods. These occurrences were not serious problems and crewmen compensated by increasing their clothing insulation.

During the Apollo 13 mission, the LM environmental control system provided a habitable environment for approximately 83 hours (57:45 to 141:05 ground elapsed time). Cabin temperature remained low due to low electrical power levels. This caused crew discomfort during much of this time, with cabin temperatures ranging between 283° and 286°K (49° and 55°F).

During the Apollo 11 mission, the crewmen could not sleep in the Lunar Module following EVA because they were too cool. Contributing to the crewmen's discomfort were the sleep positions on the floor of the vehicle, the use by the crewmen, for some time after the EVA, of a cabin supply to their liquid cooling garments that had been provided against a hot-case contingency; and vehicle temperatures between 288° and 290°K (58° and 62°F). Hammocks were provided for sleeping after subsequent Apollo EVA's, and the cabin liquid cooling garment support system was not used before the sleep period; therefore, the problem did not recur.

At the conclusion of each of the missions, the Command Module was precooled prior to reentry to minimize the possible effect of the reentry thermal transients on the internal temperature of the Command Module. No elevated cabin temperatures were experienced during any of the reentries.

Acceleration and Impact

With the exception of Apollo 7, which used the Saturn IB, all Apollo missions used the Saturn V launch vehicle. Launch acceleration loads were well within Apollo system specifications, and crewmembers routinely reported that the launches produced no adverse physiological stresses. A typical Saturn V launch profile is presented in figure 2.

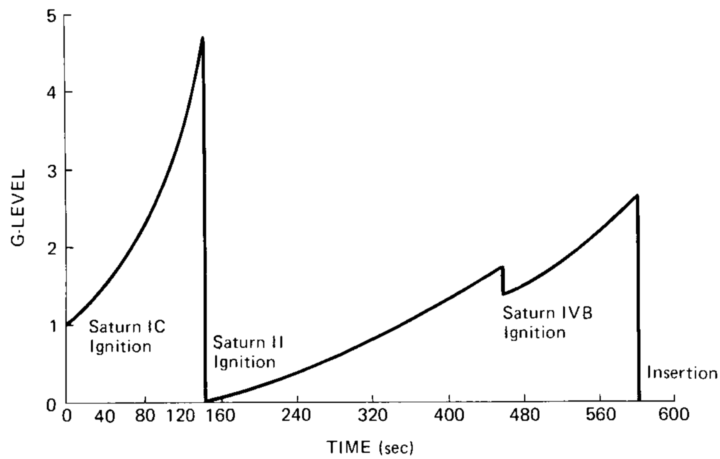

Figure 2. Typical Apollo launch profile – Saturn V launch vehicle.

Maximum reentry G levels for all Apollo missions are shown in table 2. As may be seen, deceleration levels for Earth orbital missions, Apollo 7 and 9, were about one-half those of lunar missions. Neither reentry mode resulted in any medically significant physiological stress. The greater reentry lift capability of the Apollo spacecraft over its predecessors accounts for the much lower acceleration forces. Reentry deceleration profiles of an Earth orbital and a lunar mission are presented in figures 3 and 4.

Table 2
Apollo Manned Space Flight
Reentry G Levels

Flight	Maximum G at Reentry
Apollo 7	3.33
Apollo 8	6.84
Apollo 9	3.35
Apollo 10	6.78
Apollo 11	6.56
Apollo 12	6.57
Apollo 13	5.56
Apollo 14	6.76
Apollo 15	6.23
Apollo 16	7.19
Apollo 17	6.49

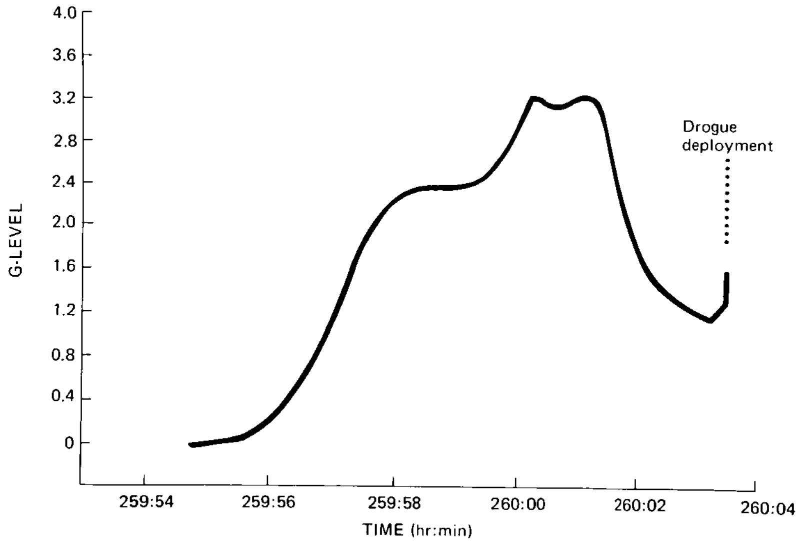

Figure 3. Earth orbital reentry profile – Apollo 7.

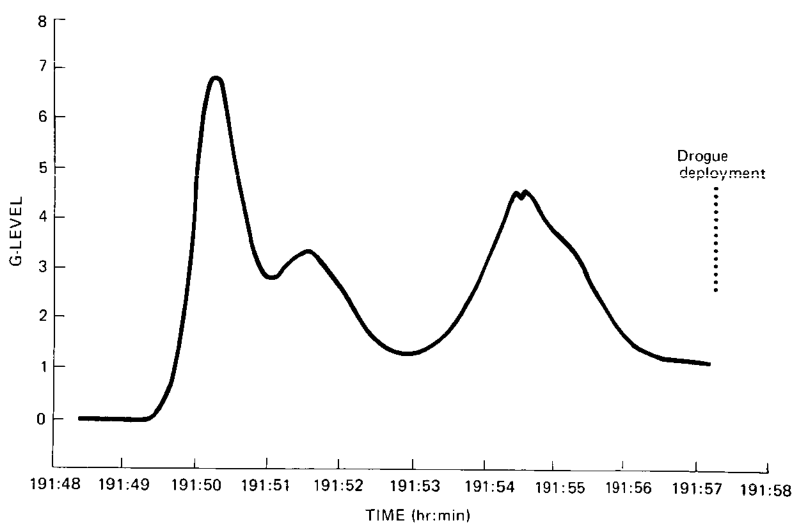

Figure 4. Lunar orbital reentry profile – Apollo 10.

While nominal reentry G levels had been well tolerated by the crew and posed no severe constraints on crew performance, an Apollo launch abort could have resulted in G_X acceleration levels as high as 16.2 G with an oscillating 1/2 Hz component ranging from $-1G_Z$ to $+3.2\,G_Z$. Such abort acceleration levels in all probability could have been endured without injury by crewmembers experienced in acceleration tests and protected by the Apollo couch and restraint system. It is very doubtful that spacecraft control tasks could have been adequately performed under such conditions and, for this reason, crew tasks were minimized during a launch abort reentry. The Apollo spacecraft abort escape system was similar to that used in the Mercury Project, consisting of an escape rocket separated from the attached spacecraft by a tower. The rocket was provided, if required to lift the Command Module away from the booster to an altitude high enough for safe parachute deployment. The escape rocket can be seen at the very top of the spacecraft (figure 5).

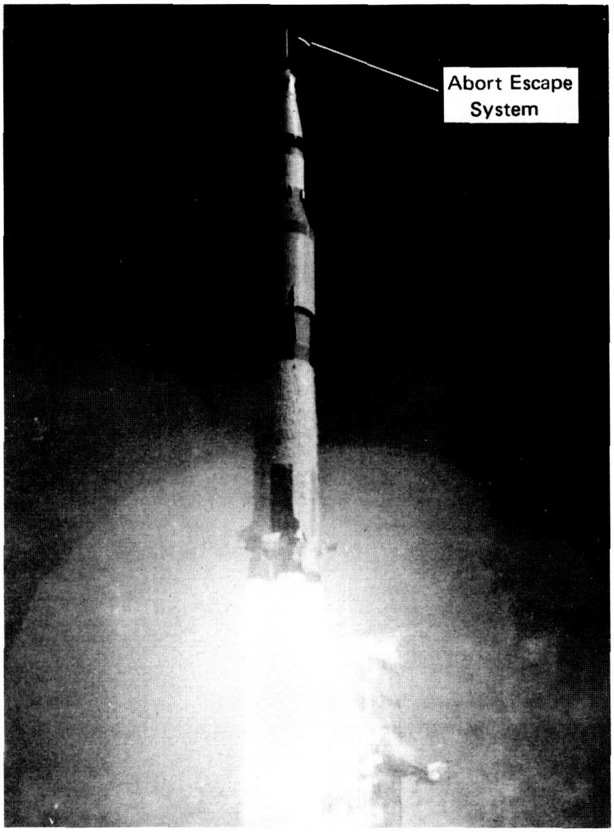

Figure 5. Apollo 17 night launch showing abort escape system at the top of the spacecraft.

The Apollo spacecraft landing system employed three parachutes and the repositioned Command Module system used in the Gemini Program (figure 6). The spacecraft entered the water at a 27 1/2^{o} angle on a nominal landing. The most severe impact experienced in an Apollo space flight occurred with Apollo 12. It was estimated that the Command Module entered the water at a 20 to 22^{o} angle which resulted in a 15 G impact. This abnormal entry angle occurred when the wind caused the spacecraft to swing and meet the wave slope at the more normal angle.

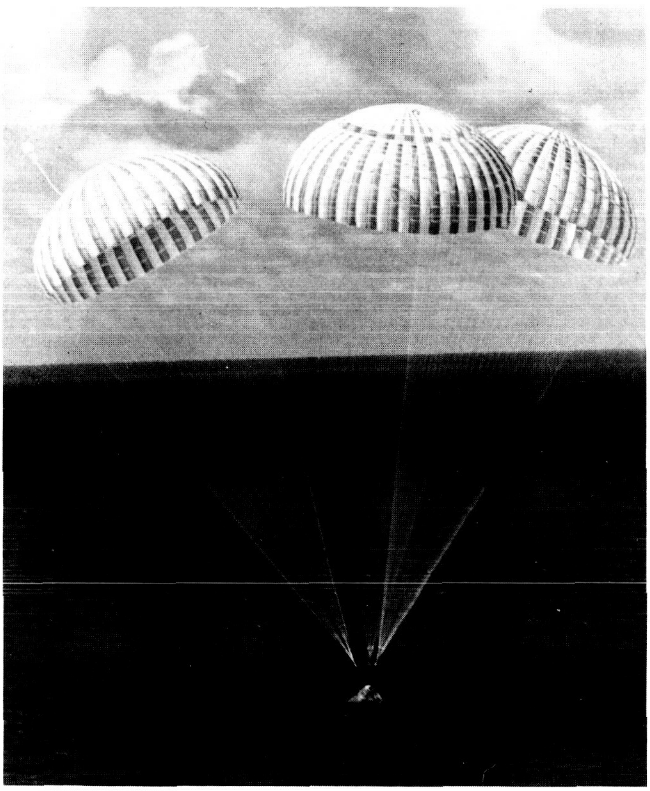

Figure 6. Apollo spacecraft parachute landing system.

While the 15 G impact of Apollo 12 was described as very hard by the crewmen, no significant physical difficulties were experienced. Apollo landing impact studies involving 288 human tests were conducted on a linear decelerating device at Holloman Air Force Base. These tests involved impact forces up to 30 G at various selected body orientations. Although significant effects to the neurological, cardiorespiratory, and musculoskeletal systems were recorded, none of the tests resulted in significant incapacitation or undue pain (Brown et al., 1966).

Summary

In summary, environmental factor considerations including atmospheric pressure and composition, thermal comfort, acceleration, deceleration and impact levels; for the most part, remained within physiologically acceptable ranges during the entire Apollo Program. At no time did an anomaly alter these factors to a point where crew health was jeopardized. The environmental changes following the Apollo 13 accident, if prolonged, would have endangered the crew. However, the quick and successful makeshift ECS modifications prevented this from occurring.

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