11. INERT GAS

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11. INERT GAS

Addition of inert diluent gas to a space cabin atmosphere alters several engineering and physiological variables which must be considered. Table 11-1 gives the physical properties of the different inert gases.

Decompression Sickness - The most significant physiological alteration determined by the inert gas environment is decompression sickness. This factor is covered in Pressure, (No. 12).

Tables 11-2, 11-3 and Figure 11-4 give some of the bio-chemical properties of the inert gases which can be used in predicting the frequency or decompression symptoms after different inert gas exposures (5, 89).

Thermal Factors

Tables 6-18 to 6-69 present the significant thermodynamic properties of the individual gases and gas mixtures of several candidate atmospheres for space cabin use (90). Figure 11-5 may be used to determine the thermal conductivity of other oxygen-inert gas mixtures. Alterations in control of body temperature, in thermal comfort zones, and in design of cabins and space suits brought about by the different inert gas environments have been covered in Thermal, (No. 6), pages 6-18 to 6-69.

Table 11-1

Physical Properties of Inert Gas

(After Roth[89])

Property	Gas					
	He	Ne	A	Kr	Xe	N_2
Atomic number	2	10	18	36	54	7
Molecular weight	4.00	20.18	39.94	83.80	131.30	28.00
Color	Colorless					
Density, gm/liter, at 0° C and 1 atm	0.1784	0.9004	1.784	3.708	5.851	1.251
Heat capacity (C_p) at 25° C and 1 atm, cal/°C-gm-mole	4.97	4.97	4.97	4.97	4.97	6.96
Specific heat ratio at 0 to 20° C, C_p/C_v	1.63	1.64	1.67	1.69	1.67	1.404
Sound velocity at 0° C and 1 atm, m/sec	970	435	319	213	168	337
Acoustic impedance at 0° C and 1 atm, dyne-sec/cm³	17.3	38.5	56.9	....	....	42.1
Thermal conductivity at 0° C and 1 atm, cal/°C-cm-sec	34.0×10^{-5}	11.04×10^{-5}	3.92×10^{-5}	2.09×10^{-5}	1.21×10^{-5}	5.66×10^{-5}
Viscosity at 20° C and 1 atm, micropoise	194.1	311.1	221.7	249.6	226.4	175.0
Critical properties: Density, gm/cm³	0.069	0.484	0.531	0.908	1.105	0.3110
Pressure, atm	2.26	26.9	48.0	54.3	58.0	33.54
Temperature, °C	−267.9	−228.7	−122.44	−63.8	16.59	−146.9

Specific references for each property are available[89].

Table 11-2

Biochemical Properties of Inert Gases

(Numbers in parentheses were calculated by Graham's law from nitrogen data)

(After Roth[89])

Property	Gas					
	He	Ne	A	Kr	Xe	N_2
Bunsen solubility coefficient in water at 38° C	0.0086	0.0097	0.026	0.045	0.085	0.013
Bunsen solubility coefficient in olive oil at 38° C	0.015	0.019	0.14	0.43	1.7	0.061
Bunsen solubility coefficient in human fat at 37° C		0.020		0.41	1.6	0.062
Oil-water solubility ratio	1.7	2.1	5.3	9.6	20.0	5.1
Relative diffusion through gelatin at 23° C	1.0	(0.42)	0.30	0.21	0.13	0.36
Diffusion constants through liquids at 37° C, $cm^2/sec \times 10^{-6}$						
Olive oil	(18.6)	(8.34)	(5.92)	(4.10)	(3.27)	7.04
Lard	(9.28)	(4.15)	(2.94)	(2.08)	(1.62)	3.50
Serum	(57.6) [a]44.4	(25.7)	(18.2)	(12.6)	(10.1)	21.7
Agar gel	(71.3)	(32.0)	(22.7)	(15.8)	(12.6)	27.0
Water	(79.2) 63.2	(34.8)	(25.2)	(17.5)	(13.9)	30.1

a Calculated from data of Ref.(38).

References for specific data points are available (89).

Table 11-3

Solubility of Nitrogen in the Blood Component

(After Van Slyke et al[108])

Component	Bunsen coefficient of nitrogen
Normal blood	0.0130
Normal plasma	.0117
Red cells	.0146
Water	.0127

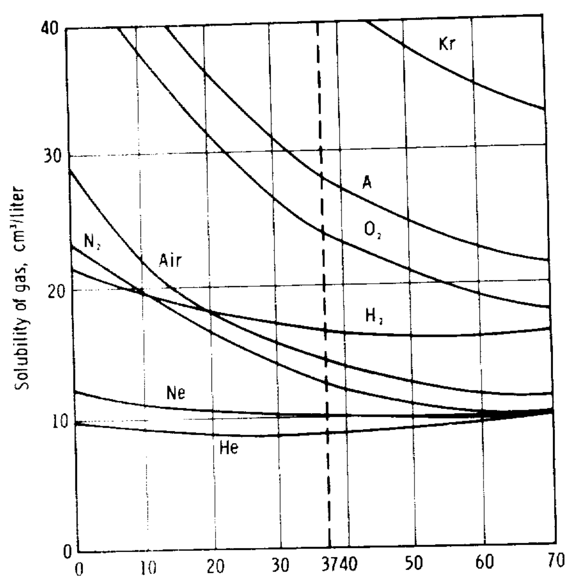


Figure 11-4

Solubility of Gases in Water at Different Temperatures

(After Tietze[101])

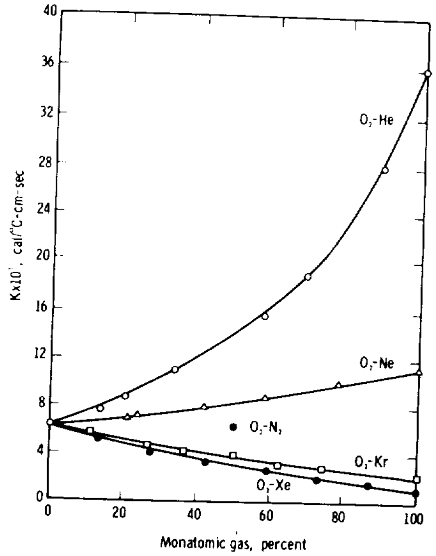


Figure 11-5

Thermal Conductivity of O_2-He, O_2-Ne, O_2-Kr, and O_2-Xe Mixtures at 30°C

(After Srivastava and Barua[96])

The temperature selected as most comfortable in several different gaseous environments is recorded in Table 6-42. No wind speed is recorded in these studies but the levels were those below the speed for rustling of paper. Uncertainties regarding comfort zones in helium-oxygen mixtures are discussed with reference to this table.

Psychrometric charts for different oxygen and oxygen-inert gas mixtures are presented in Figures 11-6 and 11-7.

Vocal Factors

Alteration of the voice by inert gas factors has been reviewed (51, 61, 89, 93). Changes in frequency can be predicted by assuming that the oronasal passages are a vibrating air column and the frequency of the sound produced by a vibrating air column is proportional to the velocity of gas/wavelength of sound. The velocity of sound, in any "perfect" gas mixture can be obtained by the equation: (102)

$$V_{sound} = \sqrt{\frac{(\gamma p)}{d}} = \sqrt{\frac{\gamma RT}{MW}} \qquad (1)$$

where T = absolute temperature

γ = ratios of specific heat

p = equilibrium pressure

γp = adiabatic bulk modulus

d = equilibrium density

R = universal gas constant

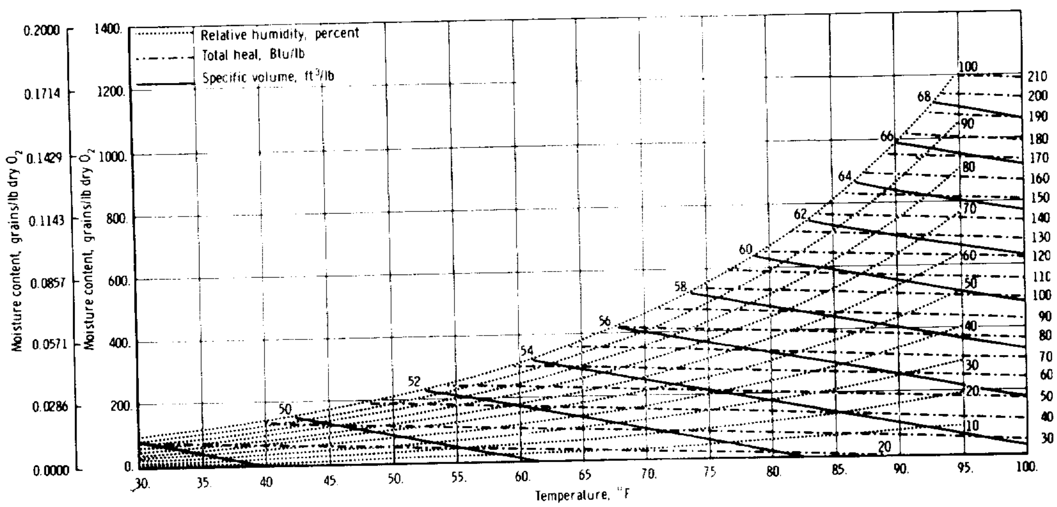
MW = molecular weight

Table 11-6

Psychrometric Chart for Oxygen

(After Green[41])

a. 3.5 psia (180 mm Hg)



b. 5.0 psia (258 mm Hg)

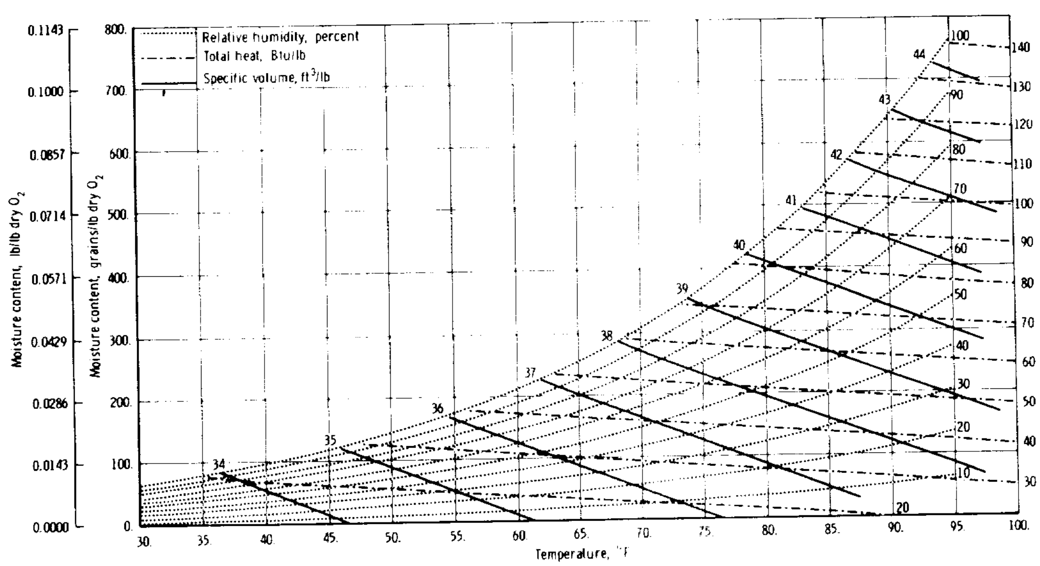


Table 11-6 (continued)

c. 5.0 to 10.0 psia (258 to 517 mm Hg)

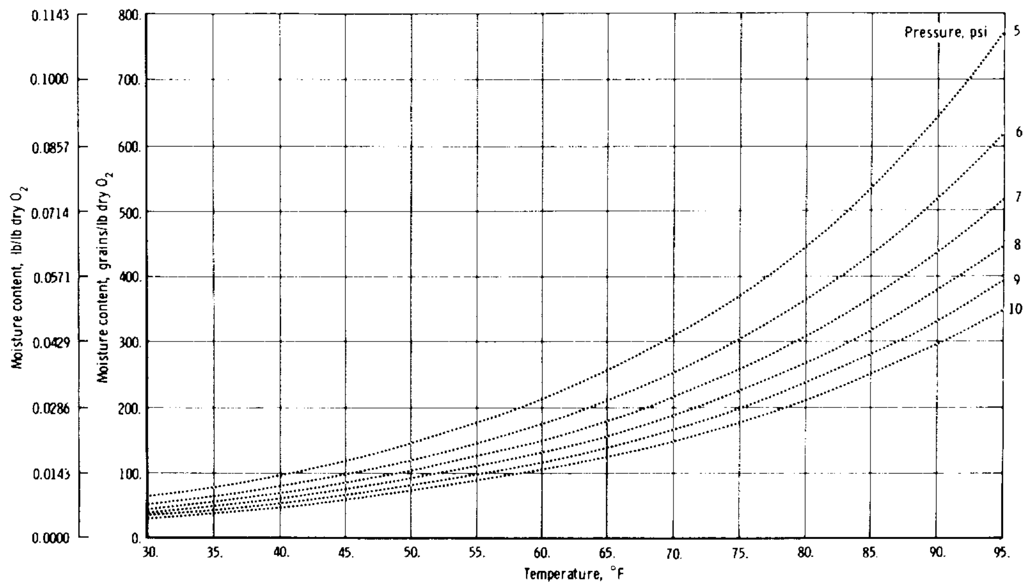


Table 11-7

Psychrometric Chart for Mixed Gases
(After Green[41])

a. Air at Sea Level (14.7 psia)

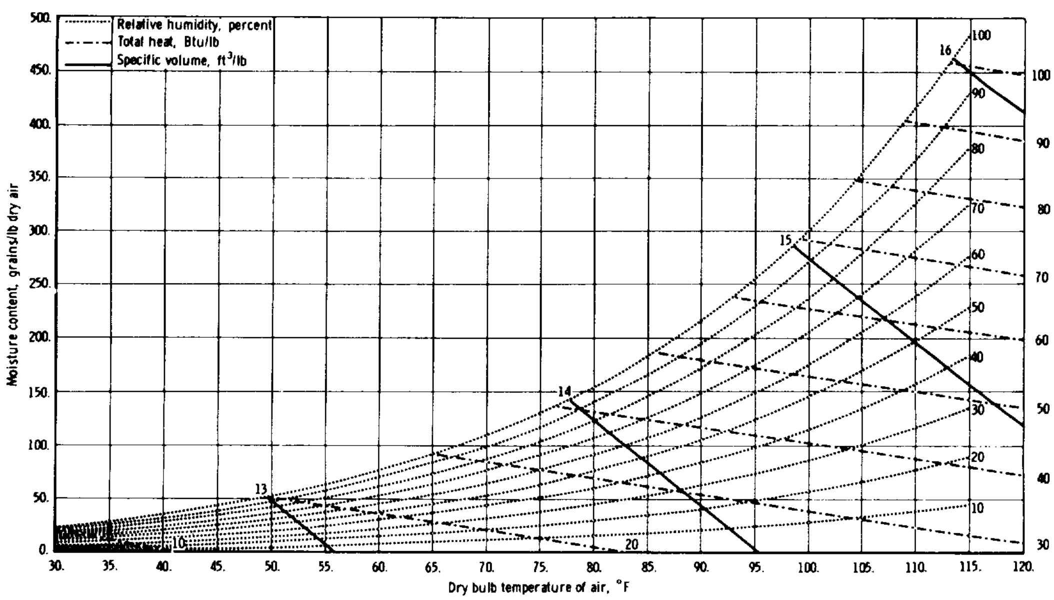
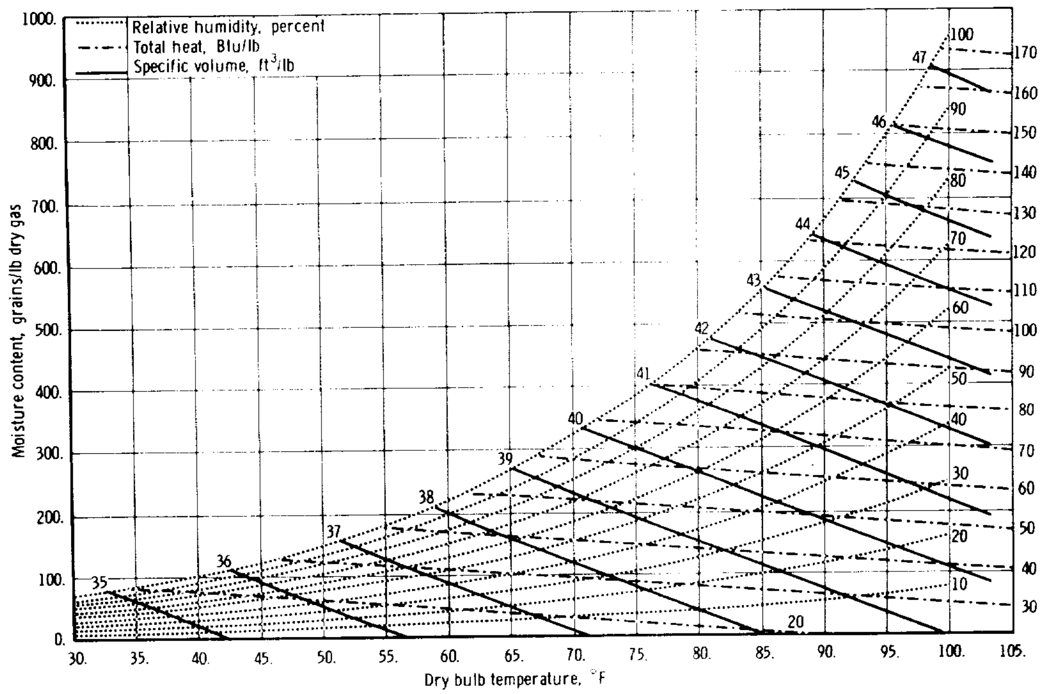
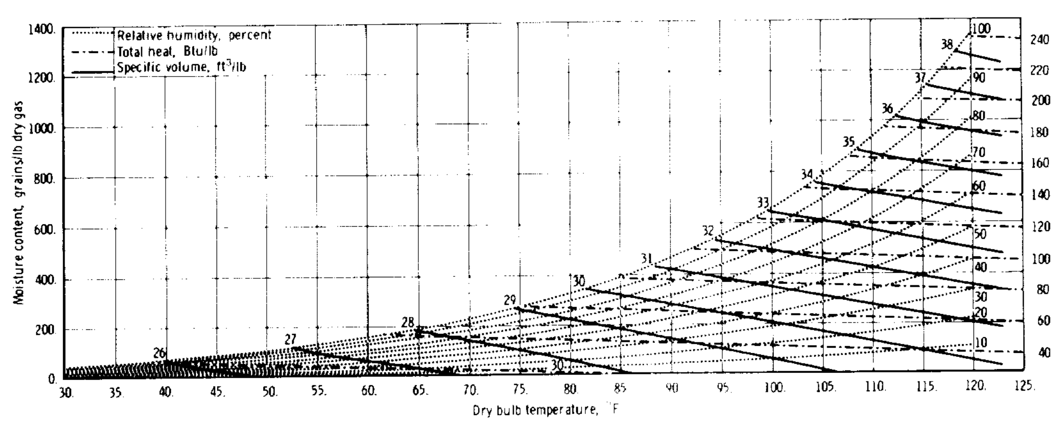


Table 11-7 (continued)

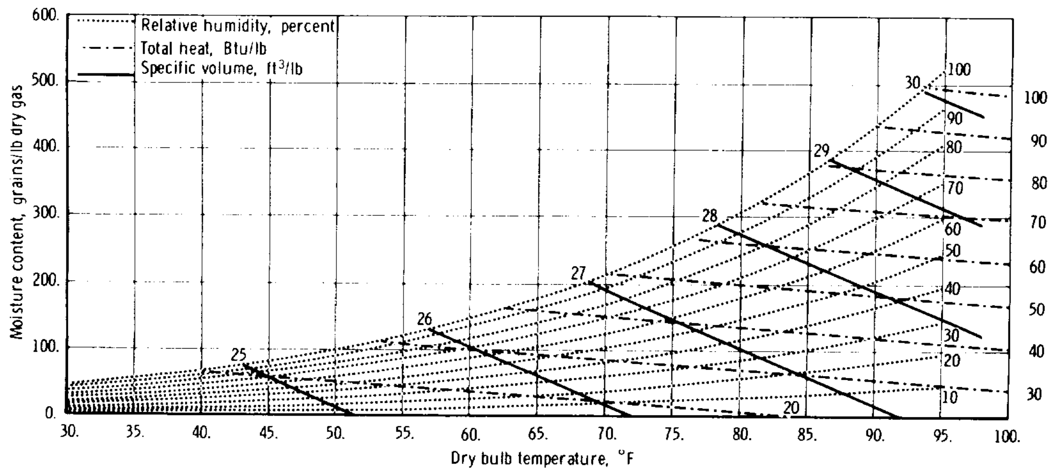
b. 70 Percent Oxygen at 3.5 psia (180 mm Hg) and
30 Percent Nitrogen at 1.5 psia (77 mm Hg)



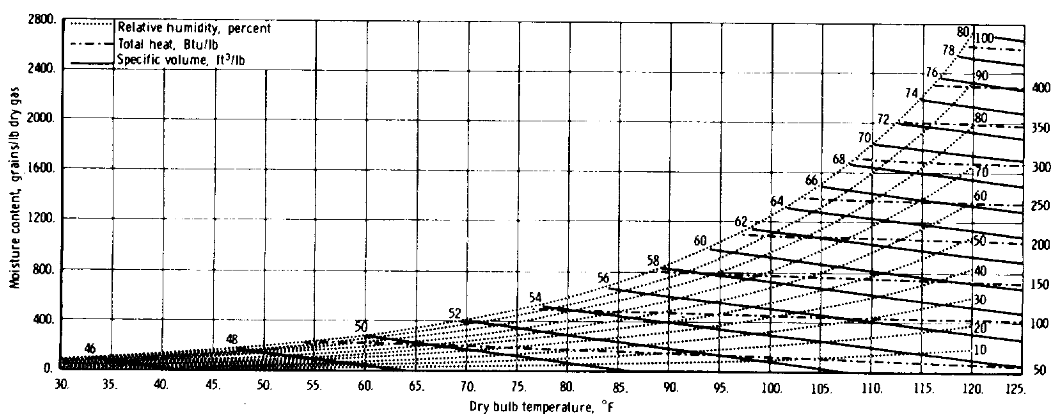
c. 50 Percent Oxygen at 3.5 psia (180 mm Hg) and
50 Percent Nitrogen at 3.5 psia (180 mm Hg)



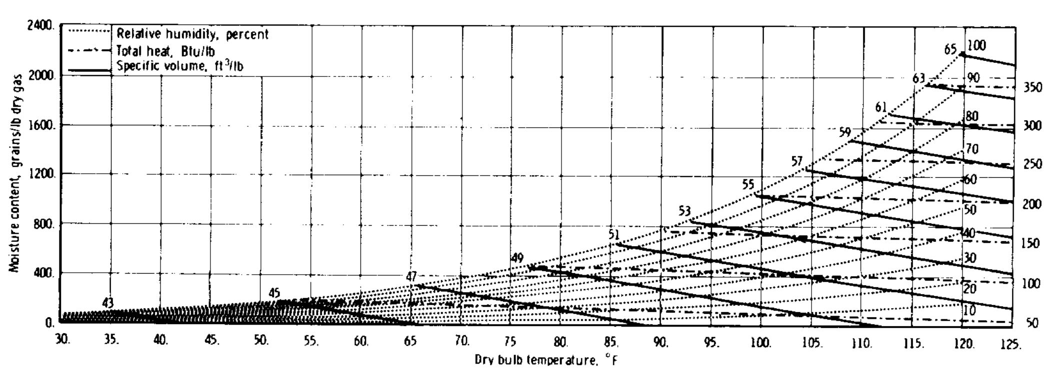
d. 47 Percent Oxygen at 3.5 psia (180 mm Hg) and
53 Percent Nitrogen at 3.9 psia (200 mm Hg)



e. 70 Percent Oxygen at 3.5 psia (180 mm Hg) and
30 Percent Helium at 1.5 psia (77 mm Hg)



f. 50 Percent Oxygen at 3.5 psia (180 mm Hg) and
50 Percent Helium at 3.5 psia (180 mm Hg)



Experimentally, this prediction of changes in frequency is altered by the audio-vocal feedback system which modifies the frequency of the vocal cords in response to the abnormal audible frequency. The resonant systems of the human are also not ideal resonating columns. Several reviews of the mechanics of phonation should be consulted for a more detailed analysis of the second-order factors in speech propagation which require further study in unusual atmospheres (16, 32, 78, 106, 110).

The low pressure and low percentage helium which can be used in a space cabin dilutes out the inert gas effect. Recent studies suggest that such helium-oxygen mixtures at low pressures create so little distortion of speech and noise as to cause no major problem in a space cabin (23, 24, 25, 74). In 56% He - 44% oxygen at 7.4 psia, there is slightly reduced intelligibility in the presence of noise. There is an increase in the mean second formant frequency of 1.35 times above that in air at S. L. In 80% He - 20% oxygen at sea level pressure this is increased to 1.6 times that of air (74). In Soviet studies at sea level pressure and 80% He - 20% oxygen, there is an increase of frequency by about 0.7 octave (30, 92). Intelligibility can be improved by simple filtering (92) and by vocoder techniques (40).

More detailed studies of voice changes, loud-speaker characteristics, and receiver or hearing patterns are under way (95).

Metabolic Factors

Alteration of the normal ratio of oxygen to inert gas for long periods of time has been thought to be of potential detriment to the human. Table 11-8 reviews all human experiments performed over periods of days in atmospheres proposed for space cabins. Similar charts for animal experiments are available (86). Oxygen toxicity is covered in Oxygen-CO_2-Energy, (No. 10).

Studies of human exposure to helium are summarized in blocks 19 to 24 of Table 11-8 (113). Slight increase in oxygen consumption is attributable to compensation for the cooling effects produced by He and bw increased evaporation resulting from the low pressure. Minor changes in plasma electrolytes, BUN, and catecholamines were accounted for by dietary changes and exercise stress. The single study on exposure of animals to neon-oxygen mixtures at atmospheric pressure suggests that unknown toxic factors in the mixtures and poor controls may have been responsible for the equivocal results obtained (119). There are no data available on the effects of chronic exposure of humans to neon-oxygen mixtures.

There are suggestions in the literature that helium may alter metabolic pathways in some biological systems (2, 13, 22, 50, 89, 117, 118). The significance of these findings to human exposure is yet to be elucidated, especially the role of nitrogen gas in normal metabolism. They may, in some way, be related to inert gas narcosis.

The pathological physiology of inert gas narcosis has been recently reviewed in great detail (10, 35, 81, 86, 89). The many hypotheses regarding the mechanism of anesthesia brought about by xenon at one

Table 11-8

Summary of Experiments in Space-Cabin Atmospherers*

Humans

(After Roth[86])

	Atmosphere*	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
1.	pO_2 190-210 P_{N_2} 20-40 2 subjects	65 to 72 hrs	None			Appeared safe in contrast to pO_2 of 578 mm Hg where bronchitis, fever and paresthesias were noted.	Becker-Freysung and Clamann[6, 7], 1942, 1950
2.	pO_2 380 10 subjects	24 hrs in full pressure suit	None			No symptoms of tracheo bronchitis as seen at pO_2 of 570 mm Hg.	Comroe [20], 1945
3.	pO_2 181 (100%) 2 subjects	3 days and 5 days in full pressure suit	Irritation of eye, nose and throat.	Normal pulmonary function tests, hematology, urinalyses and blood chemistries; decreased eosinophiles and elevated 17 Keto-steroids attributed to "stress" of the suit.	Pustular dermatitis from poor suit hygiene.	Irritation probably due to dryness.	Hall and Martin [43], and Hall and Kelley [42], 1960, 1962
4.	pO_2-418 P_{N_2}-105 (oxygen peaked transiently to 225 mm Hg) 6 subjects	7 days	Substernal tightness on deep inspiration on days 2-7; intermittent aural atelectasis; symptoms disappeared within 24 hrs after exposure terminated.	Slight decrease in vital capacity in 2 subjects; x-ray suggesting patch of atelectasis in one subject. Hemograms and urinalysis are normal.	Dermatitis due to poor clothing hygiene.	Aural and pulmonary atelectasis due to lack of nitrogen-brake effect.	Michel et al [68], 1960
5.	pO_2-150-160 P_{N_2}-220-230 5 subjects	7 days	None	Normal			Steinkamp et al [98], 1959

* All pressures in mm Hg

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
6.	pO_2-150 P_{N_2}-230 2 subjects	30 days	None	Cardiovascular changes as in # 7. No other findings.		See # 7. Unpublished data on 3 other subjects show similar findings (111).	Welch et al (112), Morgan et al (71), 1961, 1961
7.	pO_2-176 P_{N_2}-5% contamination 2 subjects	17 days	Dryness of nose and respiratory tract, eye irritation, nasal congestion for 72 hrs, then decreased as humidity rose; occasional paresthesia of calves and arms; aural atelectasis; retrosternal pain in one subject, decreased by pressure elevation.	Vital capacity decreased by 10 % at 5 days, no x-ray findings; decrease in diastolic pressure in several subjects; decreased exercise tolerance, normal orthostatic tolerance, transient abnormal EKG findings on exercise test, decrease in total body water, blood volume and plasma volume; no hemoglobin changes.		Fluid and cardiovascular defects probably due to inactivity and evaporative water loss.	Welch et al(112), Morgan et al (71), 1961, 1961

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
8.	pO_2 a) 380 b) 258 c) 196 $N_2 < 0.5\%$ 21 subjects	14 days	Weight loss; loss of appetite; occasional bends symptoms; cough on vital capacity testing; aural atelectasis; head colds and sore throats in some subjects; eye irritation; substernal discomfort; aerotitis in several subjects, coughing after MBC tests.	β-strep in throats; occult blood in stool of 1 subject; decreased mean oxygen content in 380 mm Hg suggesting abnormal hemoglobin; progressive decrease in MBC in 196 group; normal vital capacity; elevated OH steroids in 258 group; normal blood electrolytes, glucose and BUN; lack of strict anaerobic bacteria in skin; protein and casts in urine in 380 and 258 groups. Hemoglobin decreased by about 2 gm %, increased osmotic fragility, slight increase in reticulocytes; rbc microcytic, anisocytotic, occasionally spherocytic, polychromatic, normoblasts, hemoglobin-stippled, Heinz bodies, Howell-Jolly bodies, Cabot ring cells, flat Price-Jones curves; vacuolization of white blood cells; post exposure reticulocytosis.		Tricresyl phosphate, toluene diisocyanate and mercury vapor were possible contaminants in cabin. Oxidative hemolytic anemia present, renal changes unexplained. One subject with thalassemia had drop of 5 Gm% in hemoglobin.	Helvey (46), 1962
9.	Total pressure 192 ±15 pO_2 - 174 ±15 8 subjects	17 days continuous	Same as #7, plus symptoms of depression in several subjects; one case of joint pain may have not been dysbaric. Crepitant rales at posterior lower lung fields in six subjects.	Same as #7, plus arterial oxygen unsaturation in 2 or 3 of the subjects as low as 90%.		2 of these subjects reported in #7; same comments as #7; arterial unsaturation possibly caused by A-V shunting of atelectasis.	Morgan et al (70), 1963

Table 11-8

Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
10.	P_{tot}-388 P_{O_2}-199 P_{N_2}-199 4 subjects	30 days	Normal performance except for difficulty in sleeping due to noise and the expected social stress of small groups.	Slight decrease in hemotocrit (-5%) and in red cell mass (-7%) during test (?blood letting); BUN's slightly elevated with no explanation given, increased water loss via skin and respiratory tract (low pressure); no change in renal function by G.F.R., C_{PAH}, C_{osm}, and output of Na,K and Cl. Catecholamine outputs reflect social and emotional stress; decrease in pulse rate response to exercise in latter part of test reflecting insufficient programmed exercise during experiment. Early mild decrease in vital capacity and timed vital capacity for first 4 days returned almost to normal; MBC - normal altitude response. Spread of hemolytic Staph-aureus from one subject to two others.	Subjects were generally within normal clinical limits of well being.	General Electric (37), 1964.
11.	P_{O_2}-258 3 subjects completed profile	2 weeks (acceleration profiles before and after exposure).	Serous otitis media in several subjects, cleared with decongestants and valsalva maneuvers.	Decrease in scotopic peripheral vision. Subsequent study of dark adaptation (27) showed minimal decrease at this pressure of O_2 associated with increased age of subjects. Normal pulmonary mechanics and diffusion capacity; hemogram normal except for effects of blood letting, urinalysis same as controls; normal EEG and EKG; blood chemistries normal.	Cabin fire terminated study.	Hendler (47), 1963, Mammen et al (62), 1963, Critz et al (27), 1964.

Table 11-8

Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
12.	a. P_{O_2}-258 P_{N_2} ? < .25% (8) (6) aborts	72 hrs	a. 6 subjects aborted at < 25 hrs because of bends pain or dyspnea. Of the remainder 2/8 substernal discomfort, 3/8 bends pain, 3/8 earache, 2/8 conjunctival irritation, 1/8 GI upset, 1/8 occipital headache.	a. 1/8 had decrease in vital capacity of > 1600 cc with x-ray signs of atelectasis in both bases; no hemolysis; normal hemoglobin, red cell volume, serum bilirubin; normal rbc glu-6 P Dase and serum isocitric dehydrogenase. Normal LDH, normal serum glucose and lipase; normal NAD, NADP, NADPH; hyperlipemia with lactescent serum and alteration of the α/β fraction of serum lipoproteins (6 hrs after meals); vision normal (see b).	Study was primarily for vision; no causes for isocitric dehydrogenase or hyperlipemic changes are evident.	Critz et al [27], 1964, Hendler [48], 1966, DuBois et al [31], 1966, Gallagher et a [36], 1965, Nobrega et al [75], 1965.
	b. P_{O_3} 380 P_{N_2} ?<.25% (6) 14 subjects	72 hrs	b. 1/6 bilateral earaches on descent to sea level; 1/6 wheezing in chest on return to sea level; 1/6 pain in lower left chest partly relieved by antacids; 1/6 nasal congestion.	b. 1/6 had 1700 cc decrease in vital capacity with bilateral plate-like atelectasis at both bases; other tests same as a but 2 subjects had elevated isocitric dehydrogenase of unknown cause (both subjects older and of moderate alcohol intake); hyperlipemia as in (a). Visual (a and b) - normal dark adaptation, visual acuity, color discrimination, stereopsis, vertical and lateral phorias, C.F.F., retinal perimetry electroretinography and intraocular tension; diameter of retinal arteries decreased by 19% and of retinal veins, by 25%.		

Table 11-8

Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
13.	P_{tot}-259 P_{O_2}-243 P_{N_2}-5 4 subjects	14 days continuous	Similar to #14. Erythema of pharynx and crepitant rales at bases clearing with deep breathing and substernal pain.	EKG-marked sinus arrythmia with palpitations in one subject, hemogram and urinalysis normal, minimal elevation in catecholamines pre-and during experiment. Arterial P_{O_2}, A-V shunt estimate, chest x-ray, vital capacity show no evidence of significant atelectasis.	Effect of O_2 on mucous membrane and aural atelectasis are the most significant findings.	Morgan et al (70), 1963
14.	P_t-258 P_{O_2}-254 P_{N_2}-0.5 4 subjects	30 days continuous	Weight stable, nasal congestion (4/4); aural atelectasis (4/4); cracked lips; trapped intestinal gas (2/4); burning of eyes (1/4); paresthesias (1/4); nasal hemorrhage (1/4); rash (1/4); crepitant rales in bases of lung (2/4).	35% decrease in work capacity on Balke test after 30 days; normal dark adaptation; urinalysis and creatinine clearance is normal decreased forced vital capacity (-5%); increased M.B.C. (+50%); normal oxygen-carrying capacity and saturation; normal diffusion capacity and residual volumes of lungs; oxygen consumption is normal. Hematocrit reduced by 9.1% (control dropped 3.4%); normal reticulocytes, osmotic fragility, glutathione, rbc glucose-6-PDase, serum bilirubin; $T_{1/2}$ of Cr^{51} studies were normal.	No active hemolysis evident; pulmonary and aural atelectasis present; trapped gas in GI tract discomforting. Decrease in work capacity due to exercise restriction.	Herlocher et al (49), 1964, Robertson et al (82), 1964, Zalusky et al (120) 1964.
15.	Same as #14 4 subjects	Same as #14	Similar to #14	Similar to #14	Data unpublished	Welch(111), 1966

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
16.	P_{O_2}-258 No % N_2 stated as contaminant 6 subjects	20 days continuous in ventilated pressure suits	Symptoms related to suit problems with flaking of skin, discomfort in sleeping, temperature and humidity control; minor psychological factors related to small group stress.	No significant changes in hemograms, Price-Jones indices; normal osmotic fragility and mechanical fragilities and bilirubin (direct and indirect); normal reticulocytes. All pulmonary function tests normal except for slight decrease in vital capacity; no atelectasis by x-ray; normal urinalyses; no hemoglobin type A_2 or F; normal serum electrophoretic lipoprotein fractions; normal serum isocitrate dehydrogenase; normal serum haptoglobin, haptoglobin-bound hemoglobin, rbc glucose-6-P-Dase. 6-8% decrease in diameter of retinal arteries and veins.		Kellett and Coburn (57),1966, Coburn (18),1966.
17.	P_{tot}-700 P_{O_2}-233 P_{N_2}-436 4 subjects	30 days continuous	Weight stable. No complaints.	36% decrease in work capacity on Balke test after 30 days; normal dark adaptation and opthalmoscopy; normal vital capacity, MBC, diffusion capacity, residual volume, and O_2 consumption. Hematocrit decreased 6.7% (controls dropped 3.4%); other blood studies normal as in #14.	Decrease in work capacity probably due to exercise restriction. Decreased hematocrit is partly due to blood withdrawal and exercise restriction.	Herlocher et al (49), 1964, Robertson et al(82), 1964, Zalusky et al (120) 1964.
18.	P_{tot}-380 P_{O_2}-160 P_{N_2}-160 with decompression to P_{tot} 190 12 subjects	24 hr maximum. Complex protocol	Subjects experienced symptoms of dysbarism at some time in the study.		Study related only to decompression sickness. Standard exercise was 10 step-ups on a 9 inch platform every 5 minutes for 3 hrs. Subjects appear to be of a high-risk group (80).	Hendler (48),1966, Damato (28),1963

Table 11-8

Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
19.	P_{tot}-760 P_{O_2}-171 pHe-578 N_2-1.5% 4 subjects	10 hrs (1) 25 hr (1) 8 hrs (suit)(1) 24 hrs (suit)(1)	Chilliness at 18-24°C (65 to 75°F)	Lower skin temperatures than at air equivalent; reduction in thermal comfort zone of 3°C in cabin; higher gaseous temperature required in suit for comfort; less sweat loss at high temperatures in suit. Speech shifted to higher frequency by 0.70 octave with slight decrease in intelligibility. Normal auditory function.	Nervous, cardiovascular and respiratory changes were all attributed to hypodynamic environment and isolation rather than to the helium per se.	Dianov (29), Kuznetzov (59), 1964, 1964.
20.	Equilibration with P_{tot}-380 P_{O_2}-160 pHe-160 Complex protocol. 12 subjects	6 to 12 hrs; mild exercise at 35,000 ft.	Subjects experienced dysbarism (see original protocol).		Study of bends incidence after helium-oxygen equilibration. Residual tissue nitrogen appeared to combine with helium in early stages of equilibration to give joint discomfort at 18,000 ft and frank bends at 35,000 ft.	Kellett et al (58) 1966.
21.	P_{tot}-380 P_{O_2}-165 pHe-206 exercise at 100 watt work load for 1 hr every 4 days	15 days continuous	4/4 conjunctivitis which cleared when humidity was increased; 1/4 acute prostatitis.	Intermittent proteinuria in concentrated morning specimen with normal BUN, serum creatinine and creatinine clearance. Hemogram, clotting tests, liver function tests, rbc glucose 6-P Dase, and serum electrolytes were normal. Reduced treadmill time on Balke test of 1-5 minutes at 15 days. One subject had syncope with EKG changes of bradycardia and transient nodal rhythm during post ex-	Prostatitis probably unrelated to atmosphere. Deconditioning from confinement of 35 days during total experimental protocol. Pulmonary changes due to low pressure, density, and flow resistance of atmosphere.	Zeft et al (121), 1966. Robertson et al (83), 1966, Epperson et al (33), 1966

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

	Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
	4 subjects			periment tilt table orthostasis. Normal BMR; 44% increase in MBC as expected from low density of air and reduction of flow resistance; forced vital capacity decreased by 5% after ascent and returned after descent. Lung volumes and carbon monoxide diffusion capabilities normal. Skin temperatures are lower after exercise than at sea level conditions as expected from thermodynamic considerations (33, 83, 89).		
22.	P_{tot}: 258, 363 P_{O_2}: 181, 170, 170 P_{He} or P_{N_2}: 72, 185, 185 70 man flights	Up to 4 hrs equilibration in a complex protocol; unsteady state gas condition	Bends symptoms after both pHe and pN_2 exposure (see text).		Study compared bends incidence after O_2 - N_2 vs O_2 - He mixtures. Unsteady state gaseous conditions limit extrapolation to equilibrium conditions.	Beard et al (5), 1966, Beard et al, (5), 1967.
23.	P_{tot}-258 P_{O_2}-175 P_{He}-74 P_{N_2}- 2	56 days with exercise regimen	Dryness of mucous membranes (4/4); nasal congestion (2/4); conjunctivitis (3/4); increased flatus (4/4); abdominal pain from trapped intestinal gas (2/4) paresthesias with exercise (3/4); middle ear problems (0); decompression disturbances (0).	Renal studies - normal inulin, PAH, endogenous creatinine clearances, concentrating and dilution tests, 24 hr protein excretion, blood pH and bicarbonate and other electrolytes. Blood enzymes -normal glutamic dehydrogenase, no lipase; 14% decrease in LDH and slight decrease in heart isozyme; slight increase post experiment in gluc 6-P-Dase, glutathione and (continued)	Humidity problems recurred with irritation of mucous membranes. Flatal problems bothersome; no oxidative hemolysis seen; enzyme changes not significant except for unexplained SGOT and SGPT rise, no ob-	Adams et al (1), Bartek et al (4), Cordaro et al (26), Glatte et al (39), Hargreaves et al (44), Heidelbaugh et a (45), Moyer et al (72), Rodgin et al (85),

Table 11-8 (continued)

Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
4 subjects			glutathione stability associated with a 3.4% decrease in hematocrit in the post experiment period; mild elevation in SGOT and SGPT (1/4) with normal liver function. No orthostatic intolerance as seen in previous studies. Respiratory - basal O_2 and CO_2 exchange were increased (evaporative factors), vital capacity transiently lowered by 4% on ascent; slight decreased expiratory reserve volume at altitude, normal residual volume, MBC increased by 40% (decreased density) normal CO_2 diffusion capacities. Nutrition - high fecal fat (high M.P. fat coating bite-sized food) and poor energy utilization of experimental diet (88%); excessive flatus (beverages and ?fat); distension of abdomen caused pain; decrease in enterococci in stools. Bacterial -transfer of staphylococci between crew. ECG - one subject had intermittent Wolf-Parkinson-White syndrome. X-ray - mucous membrane thickening in sinuses (1/4).	vious toxic contaminants in atmosphere.	Robertson et al (83), Ulvedal et al (104), Vanderveen et al (107) Zeft et al (123), Zeft et al (122), 1966.
24. P_{tot}-360 P_{O_2}-180	30 days	See Thermal Environment (No. 6).	See Thermal Environment (No. 6).	Primarily equipment and thermal study; crew performance normal.	Bonura and Nelson (12), Secord and Bonura (94), 1967, 1965.
P_{N_2}-180 P_{tot}-250 P_{O_2}-180 pHe-70 4 subjects	5 days	Same	Same		

atmosphere and other inert gases at higher pressure invoke clathrate and hydrate formation or protein binding concepts. Abnormal metabolic factors which may arise in more prolonged exposure to He in space cabin atmospheres could have a basis in these biophysical areas. Extension of human exposure to helium-oxygen beyond 56 days (block 23 in Table 11-8) in spacecraft should probably be preceded by day-for-day simulation on the ground. Less stringent ground-based simulation will be required for oxygen-nitrogen mixtures. Criteria for selection of space cabin atmospheres will be presented below. (See Table 11-16.)

Leakage of Gas from Cabin

Slow leakage of gas in long space missions may lead to a condition in which the total pressure in the cabin must be reduced to minimize leakage so that the mission can be completed. Slow leakage will also require a specific weight penalty for make-up oxygen and inert gas. More rapid leakage after penetration of the cabin by meteroids or after accidental puncture will lead to acute hypoxia as the limiting factor. (See Pressure, No. 12.)

Major leakage from space cabins appears to arise from elastomer-to-metal hatch seals. This must be accounted for in compensatory gas storage. The mass rate of leakage is dependent on the molecular composition of the gas (11, 12, 64, 90). Selection of appropriate equations for the description of slow leaks through elastomer-metal seals has been a problem. The most divergent equations for seal-leak calculations are those for isentropic sonic-orifice flow used in the case of large holes and those for capillary, free-molecular flow. Mason's recent modification of the Knudsen equation for capillary flow of laminar continuum to free molecular transition at a final pressure of zero appears to be accepted as a reasonable approach: (64)

$$q = \frac{5.22\ D^4 P'^2}{10^6 \mu' L} + \frac{7.42\ D^3 P'}{10^6\ L}\sqrt{\frac{T'}{M'}} + \left[\frac{7.44\ D^2 \mu' T'}{10^8\ M' L}\right]\left[\ln\left(1 + \frac{23.9\ D P'}{\mu'}\sqrt{\frac{M'}{T'}}\right)\right] \qquad (2)$$

where q = pressure x volumetric leakage rate, micron-liters/sec

D = capillary diameter, microns

P' = cabin pressure, psia

μ' = viscosity, poise

L = capillary length, cm

T' = temperature, °F

M' = molecular weight (average)

The most probable hole size is in the range of 1 to 10 microns (64).

The mass leakage of helium-oxygen mixtures is much less serious than once thought. There is actually little difference between the weight of proposed gas mixtures lost per day in the 5- to 7-psia range. For orifice flow, the leakage rate is nearly proportional to pressure. At pressures less than 7 psia, the same is true for capillary flow. As the pressure and molecular weight increase, Equation (2) suggests that the leakage rate becomes proportional to the square of the pressure.

Table 11-9 compares the mass leak rate through capillaries of 3 microns in diameter for approximately similar mixtures and pressures calculated by the two independent groups using the different basic assumptions discussed previously. The leak rates appear quite insensitive to the different capillary lengths under study (1 and 6.3 mm). This remarkable agreement may have fortuitously arisen from the interaction between the slightly different pressures and compositions being studied and the differences in path length. In any case, these mass leak rates appear to be adequate for a first-order analysis of the weight tradeoffs of the different gas systems. The oxygen-neon mixtures appear to be slightly more favorable than the other mixtures for the 3-micron-diameter hole under consideration.

Table 11-9

Comparison of Mass Leakage Rates Assuming Capillary Flow

(After Roth[90])

Mass leak rate, lb/day, at pressures of—							Study
5 psia				7 psia			
100 percent O_2	70 percent O_2 30 percent He	70 percent O_2 30 percent Ne	70 percent O_2 30 percent N_2	50 percent O_2 50 percent He	50 percent O_2 50 percent Ne	50 percent O_2 50 percent N_2	
1.0	0.811	0.702	0.988	1.13	0.810	1.70	Mason et al[64]
1.05	.76	....	1.05	1.08	....	2.0	Boeing[112]
1.0	.72	....	1.00	1.02	....	1.90	Boeing[112] normalized to 5 psia O_2 = 1 lb/day

Recent experimental studies on leakage generally confirm these theoretical predictions (12). The leakage ratio, by weight, of $N_2 - O_2$ to $He - O_2$ for total cabin pressures of 5, 7, and 10 psia were 1.23, 1.66, and 1.80 respectively. Data are available on total vehicular weight penalties dictated by these ratios for specific mission types (12, 90). Recent advances in sealing technology for spacecraft design have been reviewed (103). These principles should be brought to bear on the problem.

Leakage of space suits has been studied (55). For future EVA operations, leakage rates of less than 500 standard cc/min at 3.7 psia will be required. Not all prototype suits have been able to meet this requirement (55). Rx-2 and Rx-3 hard suits have attained a leakage of less than 25/cc/minute at 5 psia - 100% oxygen. It is reported that these leak rates do not appreciably increase with time, wear, and don-doff operations as in the case of contemporary soft suits (60).

Gas Storage Penalties

In calculation of weight penalties for life-support systems of cabins or PLSS backpacks, the interior gaseous environment must be considered (90).

The following data cover the weight and volume penalties to be assumed for the high-pressure gaseous and cryogenic storage of different atmospheric constituents. The storage of solid forms of oxygen such as superoxides, peroxides, chlorates and ozonides, as well as the electrolysis of water, were covered in Oxygen-CO_2-Energy, (No. 10). (See Table 10-33.) More data are available on solid oxygen storage (90).

It should be remembered that the tradeoffs for gas tankage or storage are often most sensitive to differences in spacecraft configuration and mission plan. This arises from the dependence of storage efficiency on the size and shape of the container, be it for gaseous or cryogenic systems. Only the basic factors covering most missions will be presented. Gas storage factor for PLSS back packs are covered in Reference (80).

High Pressure Gaseous Storage

The basic role of gaseous storage systems appears to be that of supplemental storage or storage for repressurization of the cabin when long-term storage prior to use makes it more efficient, especially in smaller cabin systems. The need for high delivery rate in repressurization also favors gaseous storage. A comparison with liquid systems under these conditions is presented subsequently.

The basic problem in this approach to gas storage is the minimization of container volume penalties by the use of elevated storage pressures without incurring excessive pressure shell weight. It can be shown that if the fluid stored acts like an ideal gas, the weight of container designed to hold a given charge is essentially independent of pressure while container volume is inversely proportional to pressure. Very-high-pressure storage appears to be the ideal goal. However, gas compressibility factors begin to limit the weight efficiency of storage. At pressures above several thousands of pounds per square inch, gases become less compressible. The decrease in compressibility is less serious for helium and neon than for oxygen and nitrogen (21).

Thus as pressure is increased, overall volume penalty passes through a minimum and actually increases because of overall shell-wall thickness. Pressure-level optimization studies for oxygen storage vessels indicate an optimum storage pressure of 7500 psia for equal pressure and volume criteria. (19, 52, 56). This psia was used in the Project Mercury system (73). Optimum storage vessels for pressure up to 9000 psia are currently under study by several companies (63). These vessels will be of greater value for helium and neon where compressibility factors play a lesser role.

If the rough sizing of a vehicle volume is available, the tradeoff between storage weight and volume can be made for any vehicle design. Data on this approach are available (19, 90). In all cases, the weight of tankage, W_T, and volume of tankage, V_T, may be given equal emphasis in minimizing the product ($W_T V_T$) or either of these factors may be over-emphasized, as in minimizing the products of

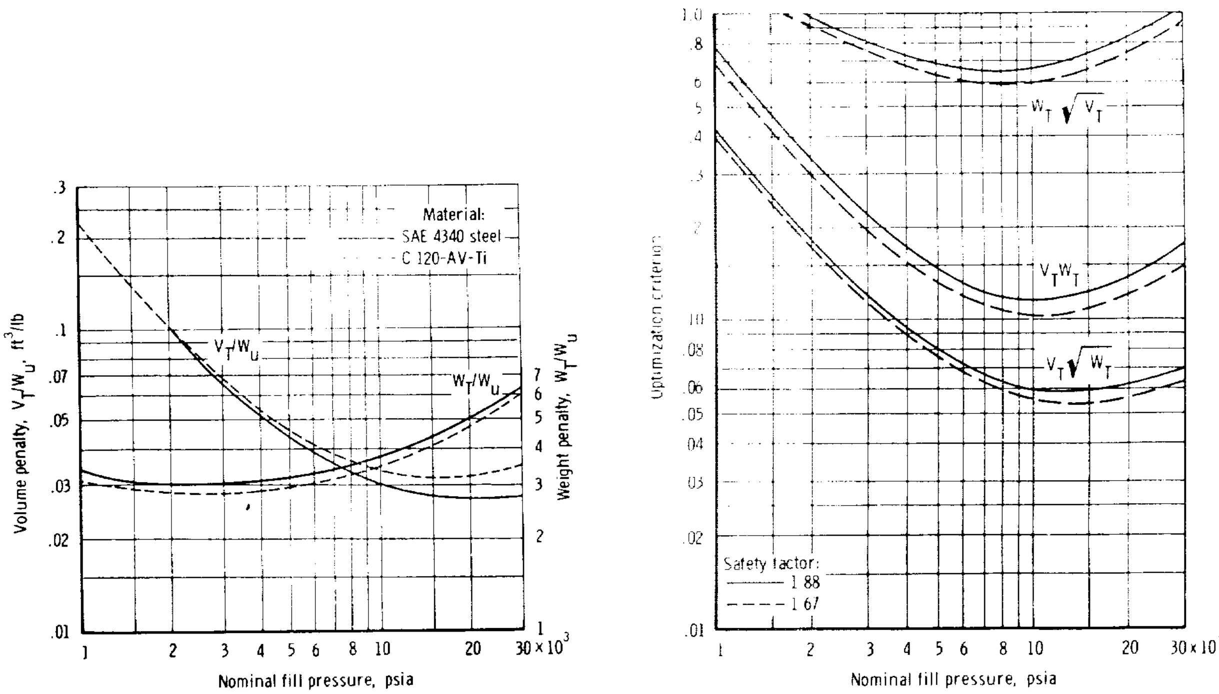
$$W_T \sqrt{V_T}, \text{ and } V_T \sqrt{W_T} \qquad (3)$$

In all cases, it is assumed that the nominal fill temperature of the vessel is 530°R and maximum fluid use is 620°R. Storage-fluid end pressure is 30 psia. The gas compressibility factors for oxygen were computed from experimental pressure-volume-temperature data for nitrogen, assuming the law of corresponding states, the accuracy of the basic nitrogen data, and the close similarity of the two gases (19). Container structural analyses were given for simple geometries and were based upon the assumptions of true geometrical shape and of a low ratio of wall thickness to diameter. It is to be emphasized that more detailed analyses than those presented would be required to optimize structural design in a specific application. Particular attention would have to be given to vessel mounting requirements.

Figure 11-10a represents the variation with nominal charge pressure of the total weight and volume of spherical oxygen vessels for SAE 4340 steel

Figure 11-10

High Pressure Gaseous Storage of Oxygen - Weight and Volume Penalties



a. Weight and Volume of Spherical Oxygen Storage Vessel for Safety Factor of 1.88

(After Coe et al[19])

b. Optimization of Spherical Oxygen Storage Vessels. Material is SAE 4340 steel.

(After Coe et al[19])

Parameter	Oxygen	Nitrogen
Optimum pressure, psia	10 500	9500
Weight penalty, W_T/W_u	3.46	3.66
Volume penalty, V_T/W_u, ft³/lb	0.0296	0.0446
Optimization criterion	0.1025	0.163

c. High Pressure Gas Storage Optimum Design

(After Rousseau et al[91])

and titanium alloy C120 AV Ti. The fire safety of titanium pressure vessels for oxygen storage has been questioned, but will be included to show the weight savings (88). A fatigue failure criterion with a safety factor of 1.88 was used.

As discussed above, the weight and volume penalties show distinct minima. Minimum weight occurs at approximately 2500-psia charge pressure, indicating the deleterious effect of charge temperature tolerances on fluid load penalties at low charge pressures. Minimum vessel volume occurs at a charge pressure of approximately 20,000 psia for the steel vessels, showing the effects of increases in vessel wall thickness at higher charge pressures, as well as the increasing compressibility factor for the gas under these conditions. From other calculations, it appears that the pressures at which the weight and volume are minimum are apparently independent of the safety factor used in the design. However, the actual values of the weight and volume are directly related to the safety factor. Similar data for Inconel 718, stainless steel 301A (cryogenically stretched by Ardeforming), and Ti 6A 6V 2S may be found in Figure 7-15 of reference (3).

Total weights and volumes of spherical nitrogen storage vessels are shown in Figure 11-11a as functions of charge pressure level cases studied. Titanium was used as the vessel material for nitrogen. The results are generally similar to those obtained for oxygen, showing minima in vessel weight and volume in the pressure range studied. Similar data covering pressure up to 3500 psia for Inconel 718, stainless steel 301A (cryogenically stretched by Ardeforming) and Ti 6A 6V 2S may be found in Figure 7-15 of reference (3). Figure 11-11b shows the terms $W_T V_T$, $W_T \sqrt{V_T}$, and $V_T \sqrt{W_T}$ for spherical nitrogen vessels as functions of charge pressure level. Here the optimum charge pressure for minimum $W_T V_T$ is approximately 8000 psia in the case considered.

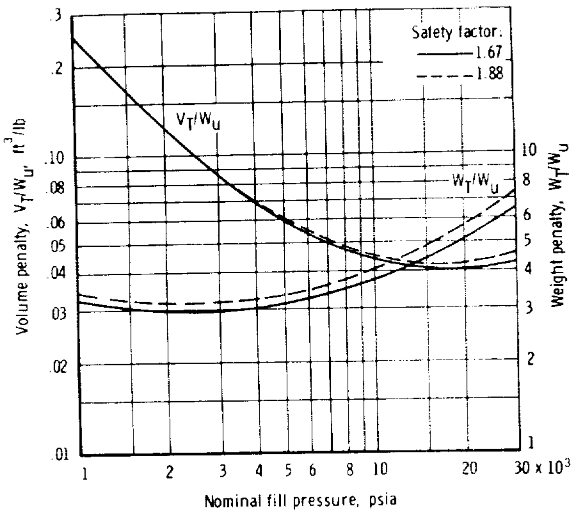
Table 11-10c summarizes the optimum values of weight and volume for oxygen and nitrogen vessels. It should be noted here that the weights plotted in Figures 11-10 and 11-11 do not include the weight of the lines, brackets, or valves; an allowance should be made for these accessories. The valve weight depends only on the number of vessels and on the number of valves installed on each vessel for redundancy and for installation requirements. Mounting bracket design depends primarily on the size of the vessel, on the number of vessels, and on the installation. These weights, in general, are small; an allowance for accessory weight should be made, however, in the total vessel weight.

The weights and volumes of spherical helium vessels are shown in Figure 11-11c as functions of charge pressure level, using titanium as the pressure shell material. These data are limited to pressures below 6000 psia because of the lack of higher pressure-density data. The tendency of helium to diffuse through the metal may well limit the usefulness of higher pressures. Compressibility is not a factor with helium.

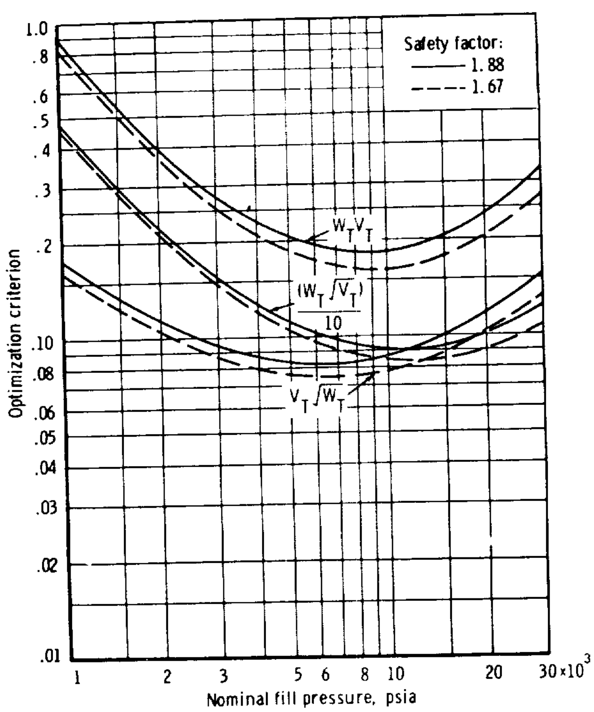
In the pressure range studied, the compressibility of neon appears to be the same as that of helium, both acting quite similar to an ideal gas (21). Since the density of helium at 0°C and 1 atm is 0.178 gm/l and that of neon

Figure 11-11

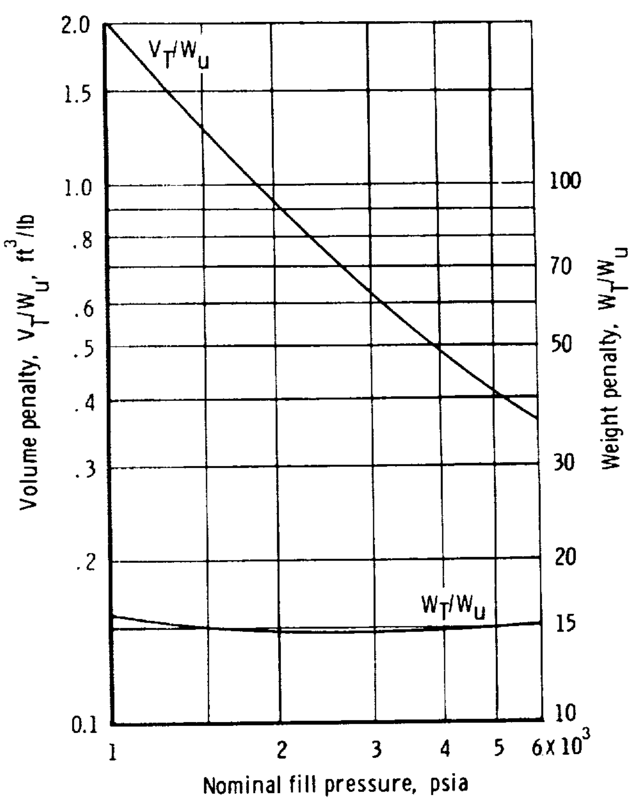
High Gaseous Storage of Nitrogen, Helium, and Neon Weight and Volume Penalties (After Coe et al[19])



a. Weight and Volume of Spherical Nitrogen Storage Vessel (Material is Ti C-120 AV)



b. Optimization of Spherical Nitrogen Storage Vessels. (Material is Ti C-120 AV)



c. Weight and Volume of Spherical Helium Storage Vessels (See text for conversion to neon)

0.899 gm/1, the volume per pound of useful load should be reduced by a factor of about 5 and run parallel to the upper curve of Figure 11-11c. Similarly, the total vessel weights per pound of useful load should also be reduced by a factor of 5 and run parallel to the lower curve of Figure 11-11c. A less expensive mixture of 85 percent neon and 15 percent helium may be economically more feasible than pure gaseous neon.

The availability of mixed gas storage in one container for repressurization purposes appears to be a great advantage of high pressure gaseous systems. This system is indeed attractive only for this purpose since the requirement for stable use of both constituents precludes its maintenance use in cabins where unavoidable erratic leaks occur. Even in the event of constant-leak systems, the mixed gas form alone is not suitable for cabins where crew occupancy or workload can vary from time to time and no parallel control of leak rate is feasible.

Cryogenic Storage

The cryogenic storage of fluids offers several distinct advantages over high-pressure storage of the low boiling-point fluids such as oxygen and nitrogen. These advantages are a higher fluid storage density at low to moderate pressure, reduced container weight per unit of stored mass, provision of potential refrigeration or cooling sources as heat sinks (170 Btu/lb for liquid oxygen or nitrogen when heated to room temperature).

The major defects are the sensitivity to unexpected heat leaks and the complexity of delivery in zero gravity. These defects require special attention to insulation needs, single-phase fluid expulsion, phase separation for venting, and quantity measurement. Cost, development time, servicing equipment, standby penalties, and limited expulsion capability are other disadvantages.

Two major classes of cryogenic liquid storage systems are used. They specify either mode of storage or method of pressurization. The fluid may be stored as a single phase of fluid or as a two-phase mixture of fluid and vapor requiring special separation techniques. The pressurization may, in turn, be accomplished by use of externally supplied gas or by thermal energy added by means of electric power or a heat exchanger in the storage space.

The following three types of systems appear to be most commonly suggested for zero-gravity space cabin use:

1) Supercritical, single-phase, thermal pressurization

2) Subcritical, single-phase, helium bladder expulsion

3) Low-pressure, two-phase, vapor or liquid delivery

Because weight tradeoffs are quite sensitive to the specific form of cryogenic storage involved, detailed knowledge of the different systems is necessary. Summaries of the different systems (19, 90) and more detailed discussions are available (17, 105).

Some of the major internal and environmental factors determining the design weight of the hardware are: (90)

1) Inner shell:
   (a) Internal fluid pressures of up to 3000 psia
   (b) Launch and reentry loads

2) Outer shell:
   (a) Compression load from buckling pressure of atmosphere
   (b) Effect of insulation and vacuum beneath it
   (c) Dynamic loads

3) Insulation:
   (a) Evacuation required to improve insulation and prevent liquefaction of atmospheric components within the space, with subsequent deterioration of performance
   (b) Temperature and pressure variation inside the craft
   (c) Compressive loads passing from outer to inner shell
   (d) Allowable heat-leak contribution from lines and support members
   (e) Ideal operational thermal requirements: no loss standby for a given holdup with pressure buildup from fill pressure to maximum pressure; constant pressure operation at minimum delivery rate with no venting in thermally pressurized tanks; and no external heat input other than vessel heat leak

It is quite apparent that all of the above factors must be considered in detail before a gas-specific cryogenic weight tradeoff can be made. Minor variation in assumptions about any of these factors can alter the cryogenic storage penalty in any specific mission.

In presenting typical cryogenic-system storage weights, the following assumptions are made:

1) Vessels are spherical.
2) Control and accessory weights are ignored; this is an important point.
3) Room temperature properties of materials are used to give weights which could be lowered if this factor becomes critical in a design tradeoff.
4) Vessel pressurization is achieved by means of electrical heaters, heat exchangers, or simply by heat leakage from the outer shell, resulting in a uniform temperature throughout the mass of the fluid stored. In practice, this condition may not be realized unless suitable means are provided for mixing the fluid inside the container, especially in a zero-gravity environment, where there are no natural convection currents. In a general analysis of the type presented here, temperature uniformity must be assumed, although in practice, a computer program can be used to cover the effects of non-uniformity of temperature (112).

5) In general, the line and support heat leaks are assumed to constitute a fixed proportion of the insulation heat leaks. This assumption greatly simplifies the calculations, since these heat leaks depend on the geometry of the lines and supports of a particular vessel and can only be calculated exactly when the detailed design of the vessel is performed. Based on previous analysis of lines and supports, it appears that the value of the ratio of line and support heat leaks selected for the numerical examples (0.20 insulation heat leaks) is conservative for large vessels, and can be achieved for small vessels by careful design of the lines and support members.

6) Heat exchangers, instrumentation, and control valves were not considered in the analysis. They are closely related to mission requirements and are therefore treated as separate components; as such, these items, together with the storage vessel itself, form a subsystem. An analysis of these subsystems has been presented elsewhere in a comparison of the total gas-system weight penalties (90). The subsystem weight should be relatively constant for different gases stored. It should be remembered, however, that for small vessels up to 10 inches in diameter, the weight of such items may in certain applications be an important part of the subsystem weight.

Other assumptions used in the numerical examples, such as constant ambient temperature, constant pressure operation, constant rate of flow, etc., are clearly stated wherever used. Details regarding the specific structure of the cryogenic systems shown in figures are available (3, 19, 90, 91). Advances in the design of new multilayered cryogenic insulation (97) may reduce these tankage penalties which should be considered to lie on the conservative side.

Figure 11-12 presents conservative weight and volume penalties for cryogenic oxygen storage and Figure 11-13 gives comparable data for cryogenic nitrogen systems.

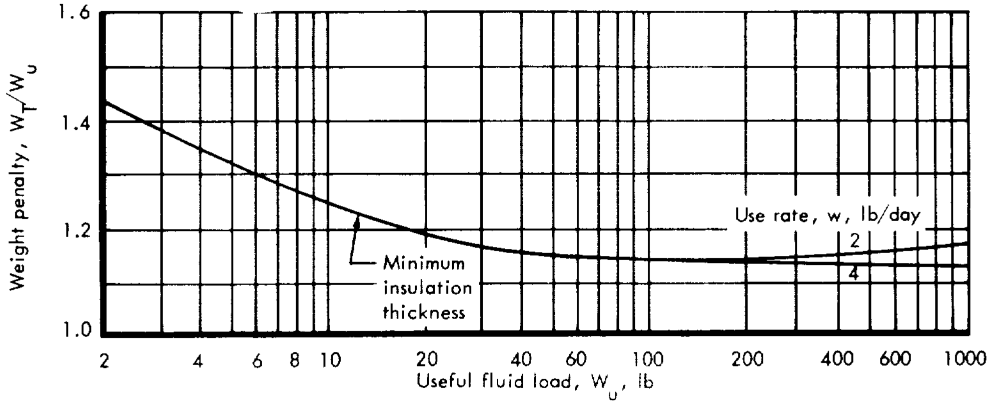
For missions of long duration, the obligatory heating of cryogenic fluid may influence tradeoff studies (3, 90). Subcritical storage initially offers weight advantages over its supercritical counterpart; however, this advantage diminishes in cases of long standby of several hundred hours and small useful fluid payloads. This is due to the fact that the quantity of heat required to pressurize the fluid from 1 atmosphere to an operating pressure of about 100 psia is only about 30 percent of that required for supercritical storage at about 900 psia. This effect is especially noticeable at small payloads where insulation presents a larger part of the total weight of the system. For long systems having long standby times, venting can be used in both supercritical and subcritical systems. In such cases, a tradeoff between vent fluid and insulation must be made. It should be stated that anticipation of such long standby times for oxygen systems is probably unrealistic, but may be realistic for inert gas systems needed to replace leakage gas in mixed gas systems.

Figure 11-12

Cryogenic Storage of Oxygen - Weight and Volume Penalties

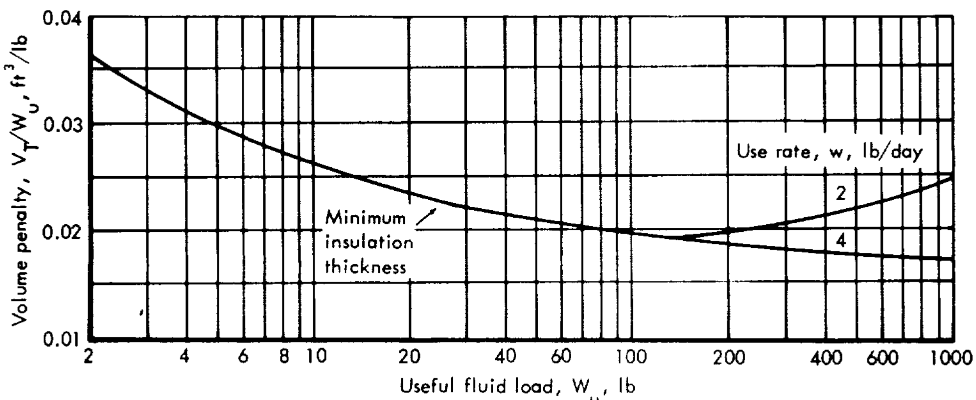
(After Rousseau et al[91])

Supercritical Storage-Spherical, Rene 41 inner shell, Al 6061-T6, outer shell, 800 psia design pressure; Subcritical Storage-Spherical, Al inner shell, Al 6061-T6, outer shell, 100 psia design pressure, helium pressurized.



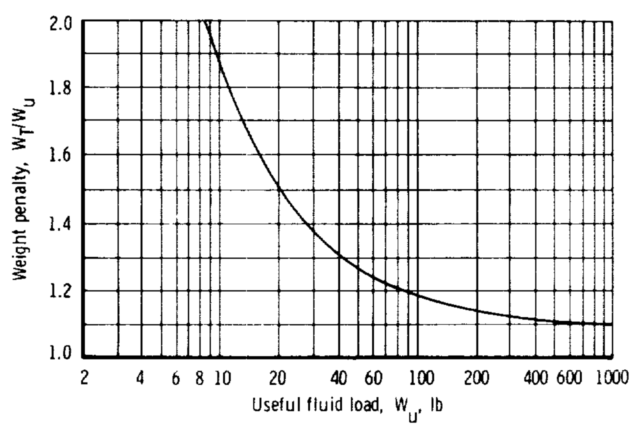
a. Tankage Weight Penalty, Supercritical Storage

Note that for flow rate higher than 4 lb/day, the vessel weight penalty is determined by the minimum insulation thickness.



b. Tankage Volume Penalty, Supercritical Storage

Note that for flow rate higher than 4 lb/day, the vessel volume penalty is determined by the minimum insulation thickness.

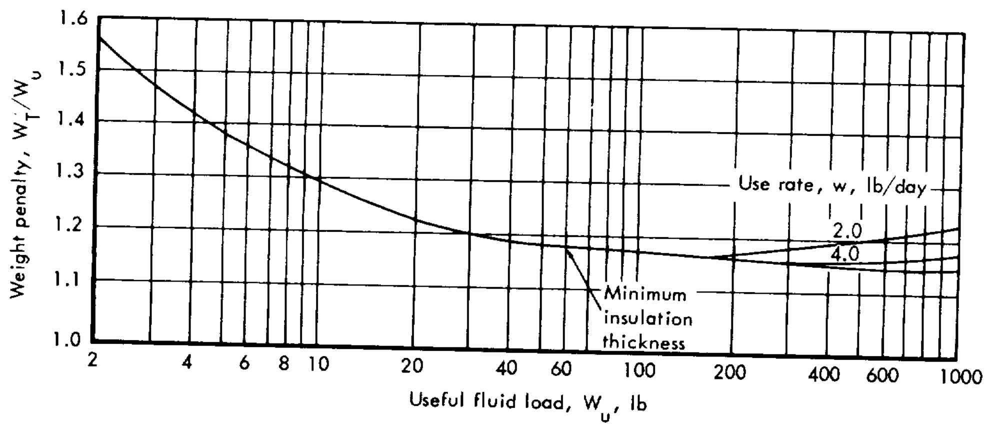


c. Tankage Weight Penalty, Subcritical Oxygen Storage

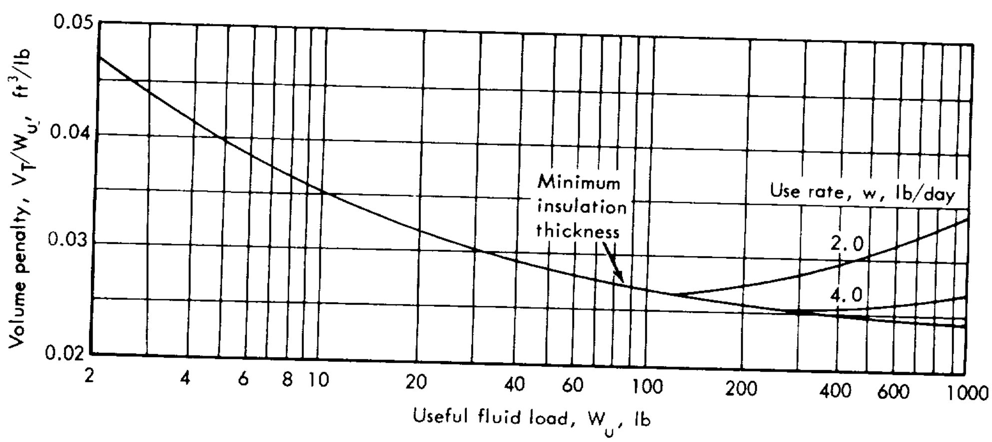
Figure 11-13

Cryogenic Storage of Nitrogen - Weight and Volume Penalties
(After Rousseau [91])

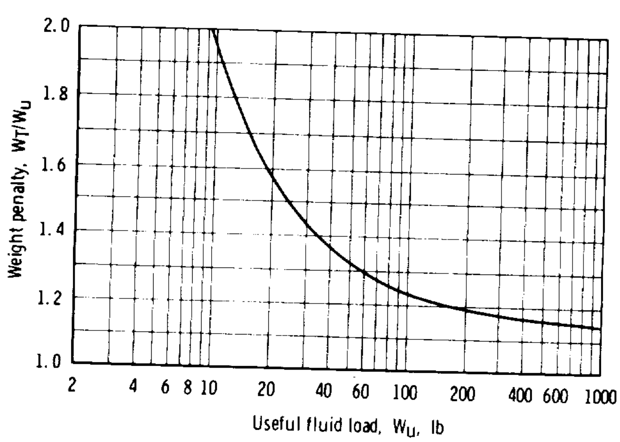
(See Figure 11-12 for design specifications of the supercritical and subcritical systems; supercritical nitrogen design pressure is 725 psia)



a. Tankage Weight Penalty for Supercritical Nitrogen Storage



b. Tankage Volume Penalty for Supercritical Nitrogen Storage



c. Tankage Weight Penalty for Subcritial Nitrogen Storage

Experience with small,flight-rated,cryogenic helium systems is limited. Because the rate of use of helium will usually be low, the heat-leak factor becomes great in determination of weight tradeoffs for helium systems (90). For example, in a 2-man 30-day mission, an error of only 1 Btu/hr in heat-leak calculation of the design can increase the total system weight by 50 pounds or nearly 50 percent (52). If the vehicle has a hydrogen tank for a fuel-cell reactant supply or for a propulsion engine, consideration should be given to mounting the helium tank within the hydrogen tank. This method results in low-temperature gaseous storage of helium with a fluid storage density comparable to that of liquid helium. The advantage is that the helium tank does not require insulation and therefore the tank design is simply a high-pressure gaseous storage vessel. A thermodynamic analysis must be made for each mission to establish the minimum expulsion rate, final density, and optimum storage pressure.

The storage of helium is particularly sensitive to use rate. Because of obligatory venting, pressure-variant methods proposed for shorter missions cannot be used in longer missions (63). In operation of the pressure-variant mode, the tank pressure is allowed to increase slowly during the mission. A portion of the energy transferred into the liquid is used to expel the demand and thereby to reduce the insulation requirement. For 30-, 60-, and 90-day missions with 2 or 3 men, the pressure-variant tanks with a maximum pressure of between 850 and 1000 psia have the same weight penalty as isobaric tanks. At first glance it would appear that tanks for the longer mission would be larger and would entail a greater weight penalty because of the same demand flow to cover a constant leak rate. However, the greater quantity of fluid stored in the longer mission allows a greater amount of energy to be absorbed by the stored cryogenic fluid per unit increase in pressure. This counteracts the other factors mentioned above. It should be pointed out that utilization of the pressure-variant mode may not be acceptable if helium is to be capable of supplying the high flow rate for compartment repressurization in the launch or orbit-stabilization phases of a space mission. At high use rates, the weight penalties will decrease. To indicate the change in penalty involved, for a 30-day 2-man mission with isobaric tank, data for helium weight penalties are plotted against use rate in Figure 11-14. The

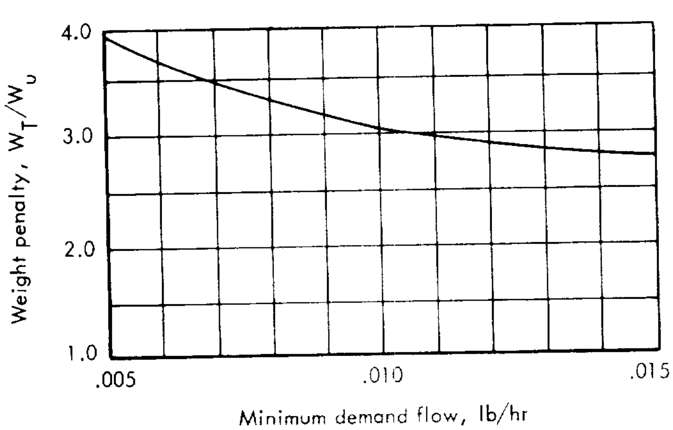


Figure 11-14

Weight Penalty Change for Cryogenic Helium Storage Due to Minimum Demand Flow

Data covers a 30-day mission, 1000 psia isobaric operation.

(After Mason and Potter[63])

W_T/W_U decreases from 3.8 to 2.75 as demand flow increases from 0.005 to 0.15 lb/hr. These rates are probably conservative figures. Work in progress on the ground-support helium tank for the Apollo lunar excursion module and on small cryogenic vessels may give a more definitive answer to weight penalties (9). Because of the lack of operational experience with small cryogenic helium systems in spacecraft and the indicated sensitivity of the system to small design errors, it would be wise to approach helium tradeoffs with great caution.

Unfortunately, little work has been done on flyable neon cryogenic systems. Small cryogenic neon units have been made for laboratory use, but no published data are available (63, 65). Neon appears to be a much more favorable liquid for cryogenic storage than is helium. Because of the high heat of vaporization and liquid density, much less boiloff of neon occurs (65). In commercial containers of 25-liter size (8 to 12 lb of liquid), the normal evaporation rate of nitrogen is 1.9, neon is 6.3, and helium is 18.1 ft^3 (STP) per day. The percentage of boiloff per day is 0.33 percent for liquid nitrogen, 0.54 percent for liquid neon, and 3.0 percent for liquid helium. The gross weights for 1000 ft^3 (STP) of gas are 92 pounds for nitrogen, 63 pounds for neon, and 31 pounds for helium. On a volume basis, neon also offers 3.5 times more refrigeration than does liquid hydrogen and 40 times more than liquid helium. Preliminary studies indicate that a subcritical system designed for 30 days of minimum leakage at 0.012 lb/hr with an initial charge of 20 pounds and a pressure-variant operating mode from 450 psia to 1500 psia will have a dry weight of only about 17 pounds (63). Therefore, $W_T/W_u = 37/20 = 1.85$ for neon compared with an optimized 3.8 for helium and about 1.2 for nitrogen.

Since the boiling point of liquid neon is above that of liquid hydrogen, gaseous storage in a liquid hydrogen tank is impossible. Because of the favorable aspects of neon from a physiological point of view, more work on the cryogenic storage of this gas appears appropriate. The problem of storage of the technical grades of neon contaminated with 15 percent helium also requires further study.

Solid lithium azide has been used as a source for generation of nitrogen gas (19). Weight penalties of W/W_{N_2} of about 1.14 on the basis of chemical material balance alone (no storage penalties for the azide or lithium oxide product) approach cryogenic storage penalties of nitrogen (Figure 11-13). In addition, the reaction is difficult to control and presents a safety problem.

Criteria for Selection of Space Cabin Atmospheres

Selection of space cabin atmosphere must be analyzed from both a physiological and an engineering point of view (87, 90). The most significant interface is the thermal. Biothermal considerations in the design of space cabins have been covered on pages 6-18 to 6-43 of the Thermal Environment, (No. 6). Some of the engineering implications are noted here.

The problem of thermal comfort in spacecraft cabins appears to be generally solved. Selection of ideal cabin air and wall temperature for any given gaseous mixture is very sensitive to the exercise rate and clothing insulation values assumed. Selection of the ideal diluent from the point of view of thermal comfort is entirely an engineering decision based on minimum weight and power. Some of the basic principles at question can be outlined. Table 6-14 presents a comparison of the thermodynamic and aerodynamic properties of the several candidate atmospheres. It can be shown that for a constant volumetric flow such as is required for removal of water vapor or trace contaminants, the blower power is approximately proportional to the density of the gas mixture ($\sim\rho$). For constant heat transfer capacity, the fan power is inversely proportional to the square of the density and to the cube of the heat capacity ($\sim 1/\rho^2 C_p^3$) (90).

From the thermal conductivity and densities of the different gas mixtures one can calculate the relative velocities required to attain the same heat transfer coefficient (h_c) and the relative power required to attain these velocities. Table 11-15 represents this comparison normalized to 7 psia 50% O_2 - 50% N_2 as equal 1. The density and thermal conductivity factors definitely favor helium-oxygen mixtures in this regard.

Table 11-15

Power Penalties for Space Cabin Ventilation and Dehumidification as Related to Atmospheric Gases

(After Boeing[11])

a. Velocities for h_{c1} = h_{c2} and Fan Power for Different Gas Mixtures

	$O_2 - N_2$		O_2 He		O_2
	7.0 psia	5.0 psia	7.0 psia	5.0 psia	5.0 psia
$k \sim$ Btu/hr-ft-°f	0.0153	0.0153	0.0386	0.0286	0.0155
$\varrho \sim$ lbs/ft³	0.0365	0.0268	0.022	0.0206	0.0279
$V \sim$ ft/min.	47.	64.	12.5	25.	60.
Power $\sim$ watts	63.	62.	10.	19.	61.
Relative power	1.	.86	.16	.30	.97

b. Power Required to Remove Water from a Gas Stream Relative to 7 Psia O_2 - N_2

	$O_2 - N_2$		O_2 - He		O_2
	7.0 psia	5.0 psia	7.0 psia	5.0 psia	5.0 psia
Power/Watts	1.00	0.72	0.60	0.53	0.72

The removal of water is a thermodynamic process which constitutes a large percentage of the thermodynamic load on the atmospheric control system (90). The amount of water vapor added by the occupants can be measured by the so-called latent heat load whereby each pound of water evaporated into the air is represented by about 1050 Btu. Latent personal heat loads of from 70 Btu/hr (resting) to about 1000 Btu/hr (severe exercise) can be expected as extreme ranges, with an average of 150 to 200 Btu/hr over a 24 hour period for each person in a multi-manned crew. The power penalties for water removal in a space cabin appear to be the major factor in determining the mass flow of the atmosphere purification system (90). The pressure drop in the system plays a major role in the gas-dependent tradeoffs. The mass flow of gas ($\dot{W}_g$) required to remove water from any atmosphere is inversely related to the specific humidity of the atmosphere (ϕ)

Therefore, comparing any 2 gas mixtures,

$$\dot{W}_{g2} \sim \dot{W}_{g1} \left(\frac{\phi_1}{\phi_2}\right) \tag{4}$$

The relative pressure drop (ΔP) for a gas flow system is related to the $\dot{W}_g$ and density (ρ) as follows:

$$\Delta P \sim \frac{\dot{W}_g^2}{\left(\frac{\rho}{\rho_{Standard}}\right)} \tag{5}$$

Since relative power for any gas may be determined by the relationship, power $\sim \dot{W}_g \Delta P/\rho$, (11)

$$Power_2 = Power_1 \left(\frac{\dot{W}_{g2}}{\dot{W}_{g1}}\right)\left(\frac{\rho_1}{\rho_2}\right)\frac{\Delta P_2}{\Delta P_1} = \left(\frac{\phi_1}{\phi_2}\right)\left(\frac{\rho_1}{\rho_2}\right)\left(\frac{\Delta P_2}{\Delta P_1}\right) \tag{6}$$.

Since it can be shown that: (90)

$$\frac{\dot{W}_{g2}}{\dot{W}_{g1}} = \frac{\phi_1}{\phi_2} = \frac{m_2}{m_1} \tag{7}$$

and

$$\frac{\rho_2}{\rho_1} = \frac{m_2}{m_1} \tag{8}$$

and

$$\frac{\Delta P_2}{\Delta P_1} = \frac{\dot{W}_{g2}}{\dot{W}_{g1}} \times \frac{\rho_1}{\rho_1} \tag{9}$$

therefore,

$$\frac{Power_2}{Power_1} = \frac{m_2}{m_1}. \tag{10}$$

Since the power required to remove a given mass of water from a gas mixture is simply proportional to the molecular weight, the relative power requirements for the different gas mixtures under consideration can be determined as shown in Table 11-15b, where the values are normalized to 7psia O_2 - N_2 as = 1.

The engineering considerations in the selection of space-cabin atmospheres appear to be dominant. A comparison of the weight, power, complexity, and cost penalties for the several atmospheres of Table 11-15 have been made (90). Weight factors include such items as: structure of cabin wall; atmospheric leakage; tankage penalties for cryogenic and superoxide storage of gas; weight and power-weight penalties for ventilation fan, atmospheric processing fan, and equipment cooling fans of the air conditioning system; and weight-dependent reliability factors. Such transient dynamic phenomena as decompression time after puncture and physiologic or equipment overloads resulting from failure of the environmental control system must also be included. A key factor in an engineering evaluation is the relative weights and complexities of such power sources as fuel cells, solar cells and nuclear systems. The economic factors in choice of atmosphere are development time, maintenance, convertibility, crew acceptance, and cost.

Unfortunately, the nature of the specific mission in question plays an overwhelming role in coloring the engineering factors. One atmosphere cannot be selected as ideal for all missions. The weight penalties are especially sensitive to the mission factor. For a 2-man orbiting laboratory of 30 days duration, up to 200 lbs. of weight may be saved by selection of the ideal atmosphere. In the example just chosen, 5 psia 30% helium - 70% oxygen gave the minimum penalty and 7 psia 50% nitrogen - 50% oxygen gave the maximum penalty (90). The penalty for neon-oxygen was almost exactly the same as that for the ideal helium-oxygen. What is gained in the more efficient cryogenic storage of neon is lost in the less efficient power utilization in the air condition system. What is quantitatively true for this case may not be true for other mission types though there would be a general trend in the above direction.

Tables 11-16a, b, and c summarize the factors which must be considered in selection of space cabin atmospheres.

Atmosphere Control

Presence of an inert gas in a space cabin mixture complicates the control of space cabin atmospheres. A cabin with 5 psia oxygen can have a control system based on a simple sensor for total cabin pressure. As oxygen is consumed and carbon dioxide is absorbed, the cabin pressure drops and more oxygen is allowed to enter the cabin to offset this pressure drop. Mixed-gas cabins require partial-pressure sensors for one of the two gases in order to maintain a constant percentage of both gases in the face of simultaneous oxygen consumption by the crew and variable, mixed-gas leakage from the cabin.

Many different P_{O_2} sensors are available, but no device with ruggedness and long-term reliability of the simple anaeroid sensor of the 5 psia oxygen system has been developed (79). A flyable, ultraviolet-absorption P_{O_2} meter is currently under development for the NASA (77). There are still some unresolved problems in the area of the interference by water vapor and carbon dioxide in the ultraviolet band being sampled. Polarographic sensors all appear to have a limited duration of performance without adjustments or

Table 11-16

Criteria for Selection of Space-Cabin Atmospheres

(After Roth(90))

a. Physiological Factors

FACTOR [a]	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER [b]
1. Aural atelectasis 10, 11	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
2. Pulmonary atelectasis 10, 11	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
3. Vital Capacity reduction 10	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
4. Hemolytic anemia 10, 11	No Problem	No Problem	No Problem	No Problem	Has occurred in lab; ? significance	(1 2 3 4) 5
5. Urinary abnormalities 10, 11	No Problem	No Problem	No Problem	No Problem	Has occurred in lab ? significance	(1 2 3 4) 5
6. Radiation Sensitivity 3	No Change	No Change	No Change	No Change	No change at this pressure	(1 2 3 4 5)
7. Voice Pitch Change 11	Insignificant	Minimal	Insignificant	Minimal	Insignificant	1 (3 5) (4 2)
8. Decompression time prior to symptoms of hypoxia 12	Longest available	Intermediate	Next to shortest	Shortest available	Intermediate	1 (5 2) 3 4
9. Alteration of trace contaminant effects 13	None expected	None expected	None expected	None expected	Has occurred in lab	1 2 3 4 5
10. Abdominal gaseous distress 11	Least, same as 2	Least, same as 1	Most, same as 4 and 5	Most, same as 3 and 5	Most, same as 3 and 4	(1 2) (3 4 5)
11. Decompression Sickness						
a) Bends 12	Rare but most susceptible	Same as 1	Very rare intermediate susceptibility	Same as 3	Probably will not occur when fully denitrogenated	5 (4 3) (1 2)
b) Neurocirculatory collapse 12	Extremely rare; most susceptible	Extremely rare; Intermediate susceptibility	Very extremely rare	Insignificantly low possibility	Probably will not occur when fully denitrogenated	5 4 3 2 1
c) Ebullism survival time 12	Least time	Intermediate time	Intermediate time	More time	Most time	5 4 (2 3) 1
12. Explosive Decompression 12	Extremely rare; most susceptible	Extremely rare; low susceptibility	Extremely rare; Intermediate susceptibility	Extremely rare; lowest susceptibility	Extremely rare; Intermediate susceptibility	4 2 (3 5) 1

Continued on next page

Table 11-16 (continued)

a. Physiological Factors (continued)

FACTOR [a]	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION ORDER [b]
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	
13. Blast overpressure **7, 12**	Intermediate lung damage; worst gas emboli	More favorable than 1	More lung damage; less dangerous emboli than 1	More lung damage; less dangerous emboli than 2	Same lung damage; less dangerous emboli than 3.	(2 4) 5 3 1
14. Flash blindness from meteoroid penetration. **2**	Least dangerous	Same as 1	Intermediate	Intermediate	Most dangerous	(1 2) (3 4) 5
15. Possible metabolic side effects **11**	Least	Slightly more than 4	Slightly greater than 1	Slightly less than 2	Most likely	1 3 4 2 5
16. Tolerance of high air temperature **6, 11**	Least	Most	Slightly more than 1	Next to 2	Same as 3	2 4 (3 5) 1
17. Changes in bacterial flora of skin and mouth **11, 13**	Least	Same as 1	Much less expected than in 5	Much less expected than in 5	Does occur in lab	(1 2) (3 4) 5

a. Bold faced numbers refer to sections of the compendium where the problem is covered.
b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

b. Fire and Blast Hazards

FACTOR [a]	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER [b]
1. Burning rate of fabrics and plastics	Slowest rate	Greater than 1 but hardest to ignite by contact with hot solid	Slightly greater rate than 2	Greater than 3 but harder to ignite by contact with hot solid	Fastest burning rate	(2 1) (4 3) 5
2. Flame temperature of burning hydro-carbon vapor.	Lowest	Probably same as 1	Slightly higher than 1	Probably same as 3	Highest	(2 1) (4 3) 5
3. Decompression time to extinguish flame.	Longest	Intermediate	Next to shortest	Shortest	Intermediate	4 3 (2 5) 1
4. Selectivity of cabin materials	Least restrictive	Same as 1	Intermediate	Same as 3	Most restrictive	(2 1) (4 3) 5
5. Flash oxidation from meteorite penetration	Least dangerous	Slightly more dangerous than 1	Slightly more dangerous than 1	Slightly more dangerous than 3	Most dangerous	1 2 3 4 5
6. Reduction of fire hazard by zero-gravity	Slightly more reduced than 3	Probably most reduced; most diffusible inertant at flame front.	Slightly less than 4	Slightly less than 2	Markedly reduced but least susceptible to zero-gravity effects	2 4 1 3 5
7. Toxicity of oxida-tion products of atmosphere.	Most toxic; oxides of nitrogen	Least toxic	Slightly less than 4	Least toxic	Same as 4	(2 4 5) (3 1)
8. See # 13 in Table c	----	----	----	----	----	----
9. Overall fire hazard	Least severe	Same as 1	Intermediate	Intermediate	Most severe	(1 2) (3 4) 5

a. Source - Reference 11-91.
b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

Table 11-16 (continued)

c. Engineering Factors for 30-Day, 2-Man Mission - Other Missions May Have Other Factors

FACTOR [a]	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER [b]
1. Gas Storage						
Overall tankage weight penalty	Less than 2)	Greatest	More than 5)	Less than 1)	Least	5 3 4 1 2
Weight of diluent gas used	Most	Slightly more than 4)	Slightly less than 1	Least used	None	5 4 2 3 1
Total gas storage weight.	Most	Intermediate	Intermediate	Least	Slightly more than 4)	4 5 (2 3) 1
2. Fan Power Weight						
Atmosphere control	Most	Slightly more than 4	Intermediate	Least	Intermediate	4 2 (3 5) 1
Ventilation and heat transfer	Most (same as 3 and 5)	Least	Most (same as 1 and 5)	More than 2	Most (same as 1 and 3)	2 3 (5 4 1)
3. Controls, weight and complication	More complicated than 5	Same as 1	Same as 1	Same as 1	Least weight and complication	5 (1 2 3 4)
4. Total ECS weight penalty	Most	Intermediate	Intermediate	Least	Intermediate	4 5 (2 3) 1
5. Development time and cost	Intermediate	High	Intermediate	Slightly more than 2 (if small diluent tankage)	Least	5 (1 3) (2 4)
6. Reliability of hardware	Less than 5	Less than 1	Same as 1	Less than 3	Most	5 (1 3) (2 4)
7. Compatability with current re-entry modules	Least	Same as 1	Intermediate	Intermediate	Most	5 (3 4) (1 2)
8. Sensitivity to extension of active missions to 90 days	Little	Some increase in storage efficiency less than 4	Little	Value does gain slightly because of increased storage efficiency.	Little	4 2 (1 3 5)
9. Sensitivity to stand-by operations	Gaseous storage insensitive, cryogenic is same as 3 and 5	Sensitive due to greater heat sink of cryogenic helium; gaseous may leak at high pressure.	Same as 1	Slightly greater than 2 due to greater heat leak; gaseous may leak at high pressure.	Same as 1	(1 3 5) 2 4

a. Factors are discussed in sections 6 and 11 of this compendium and in References 11-12 and 11-90.
b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

replacement of the sensor elements (54). Chromatographic techniques are available but these are costly in terms of weight and are not as reliable as might be desired in flight equipment. A flyable chromatograph is under development (114, 115). Time-of-flight mass spectrometers also have the same problems of reliability and flight worthiness (8). Mass-spectrometers suitable for flight operations are also under development, but no reliability data are available as yet (63, 76).

Fuel-cell sensors have been developed which may operate as part of the hydrogen-oxygen fuel cell of the main power supply or be self-contained instruments. Again, no reliability data are available. Flyable hardware is now under development (109).

Two new approaches to flyable,oxygen-sensing devices appear encouraging. A zirconium-oxide, solid-electrolyte cell with high temperature operation is under development (99) as are thin-film gold and zinc oxide processes (15 116). No reliability data are as yet available.

Sensing inert gas components is another approach to the problem. Helium, by virtue of its unusual physical properties, presents the greatest opportunity for flyable instrumentation. Such physical approaches as thermal conductivity, sound resonance, mass and coincidence spectrometry, and others, offer good potential, but no flight hardware has been developed. An ionization gage has been developed for analysis of helium-oxygen mixtures in gas dynamics laboratories (66). In spite of the complexity of the circuitry, the modification of such a device for spacecraft use may be a fruitful approach.

A thermal conductivity meter has been used in physiological experiments to separate helium from other respiratory gases and contaminants (67). An acoustic gas analyzer has also been used in respiratory physiology (34).

The weight penalty and reliability factors associated with the additional controls as well as the sensors in mixed gas systems must also be accounted for. Several control instruments for mixed-gas control are available (14, 69). It has been estimated that additional weight for a mixed-gas control above that for 5 psia oxygen will range from 12 to 15 pounds (53). It has also been estimated that for the Apollo spacecraft, substitution of a 7 psia oxygen-nitrogen system for the present 5 psia system would increase the total gas systems weight penalty, including sensors, controls, and tankage, by only 52 pounds or about 10 percent (63).

Studies are underway to establish analytic techniques for control of atmospheres and other components of integrated life-support systems (100).

REFERENCES

11-1. Adams, J. D., Conkle, J. P., Mabson, W. E., The Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. II. Major and Minor Atmospheric Components, SAM-TR-66-253, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 555-558, June 1966.

11-2 Allen, S. C., Role of Nitrogen in Problem of Oxygen Toxicity, The Physiologist, 4: 2, 1961.

11-3. Balinskas, R. J., Manned Orbiting Space Station. Vol. 4. Environmental Control and Life Support System Study, Final Report, NASA-CR-65088, May 1964.

11-4. Bartek, M. J., Ulvedal, F., Brown, H. E., Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. IV. Selected Blood Enzyme Response, SAM-TR-66-246, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in Aerospace Med., 37: 563-566, June 1966).

11-5. Beard, S. E., Allen, T. H., McIver, R. G., Bancroft, R. W., Comparison of Helium and Nitrogen in Production of Bends in Simulated Orbital Flights, Aerospace Med., 38: 331-337, Apr. 1967.

11-6. Becker-Freyseng, H., Physiological and Patho-Physiological Effects of Increased Oxygen Tension, in German Aviation Medicine in World War II, U. S. Air Force, 1950, Vol. I, Chapt. V-E, pp. 493-514.

11-7. Becker-Freyseng, H., Clamann, H. G., Die Wirkung Langdaurender Sauerstoffatmung in Verschiedinen Höhen auf den Menschen, Luftfahrtmedizin, 7: 272, 1942.

11-8. Beckman Instruments, Inc., Proposal for Gas Analyzer, Rept. CS-62-227, Fullerton, Calif., 1962.

11-9. Beech Aircraft Corp., Unpublished Data on Cryogenic Storage of Helium, Boulder, Colo., 1967.

11-10. Bennett, P. B., The Aetiology of Compressed Air Intoxiciation and Inert Gas Narcosis, Pergamon Press, London, England, 1966.

11-11. Boeing Company, ECS Flight Technology Group: Engineering Tradeoffs of Different Gas Systems Pertaining to the Selection of Space-Cabin Atmospheres, Seattle, Wash., unpublished data, 1965.

11-12. Bonura, M. S., Nelson, W. G., Engineering Criteria for Spacecraft Cabin Atmosphere Selection, NASA-CR-891, Sept., 1967.

11-13. Boriskin, V. V., Oblapenko, P. V., Rol'nik, V. V., et al., The Possibility of Growth of an Animal Organism under Conditions of Replacement of Atmospheric Nitrogen by Helium, Doklady Akademii Nauk SSSR, 143 (2): 475-478, Mar. 1962.

11-14. Bostick, C. R., AiResearch Mfg. Co., Division of Garrett Corp., Department 93-3, Los Angeles, Calif., personal communication, 1965.

11-15. Burger, R. M., Canady, K. S., Wortman, J. J., A Study of Thin Film Partial Pressure Gas Sensors, NASA-CR-66306, Feb. 1967.

11-16. Cavagna, G. A., Margaria, R., An Analysis of the Mechanics of Phonation, J. Appl. Physiol., 20(2): 301-307, Mar. 1965.

11-17 Christian, J. L., Hurlich, A., Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment. Part II. ASD-TDR-62-258, Pt. 2, Aeronautical Systems Div., Wright-Patterson AFB, Ohio, Aprl. 1963.

11-18. Coburn K. R., Report of the Physiological, Psychological, and Bacteriological Aspects of 20 Days in Full Pressure Suits, 20 Days at 27,000 Ft. on 100% Oxygen, and 34 Days of Confinement, NASA-CR-65394, Apr. 1966.

11-19. Coe, C. S., Rousseau, J., Shaffer, A., Analytical Methods for Space Vehicle Atmospheric Control Processes, ASD-TR-61-162, Part II, Aeronautical Systems Div., Wright-Patterson AFB, Ohio, Nov. 1962.

11-20. Comroe, J. H., Jr., Dripps, R. D., Dumke, P. R., et al., Oxygen Toxicity: The Effect of Inhalation of High Concentrations of Oxygen for Twenty-four Hours on Normal Men at Sea Level and at a Simulated Altitude of 18,000 Feet, J. A. M. A., 128: 710-718, Jul. 1945.

11-21. Cook, G. A. (ed.), Argon, Helium, and the Rare Gases: The Elements of the Helium Group. Vol. I: History, Occurrence, and Properties, Vol. II: Production, Analytical Determination, and Uses, Interscience Publishers, N. Y., 1961.

11-22. Cook, S. F., South, F. E., Jr., Helium and Comparative in Vitro Metabolism of Mouse-tissue Slices, Amer. J. Physiol., 173: 542-544, June 1953.

11-23. Cooke, J. P., Communication and Sound Transmission in Helium and Various Gases at Reduced Pressures, Aerospace Med., 35: 1050-1053, Nov. 1964.

11-24. Cooke, J. P., Sound Transmission in Helium and Various Gases at Low Pressures, SAM-TDR-64-43,School of Aerospace Medicine, Brooks AFB, Texas, May 1964.

11-25 Cooke, J. P., Beard, S. E., Verbal Communication Intelligibility in Oxygen-Helium, and Other Breathing Mixtures at Low Atmospheric Pressures, SAM-TR-65-269, School of Aerospace Medicine, Brooks AFB, Texas, Dec. 1965. (Also in Aerospace Med., 36: 1167-1172, Dec. 1965).

11-26. Cordar, J. T., Sellers, W. M., Ball, R. J., et al., Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. X. Enteric Microbial Flora, SAM-TR-66-125, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in Aerospace Med., 37: 594-596, June 1966).

11-27. Critz, G. T., Mammen, R. E., Gifford, E. C., et al., Problem Assignment No. 005AE13-24, Effect of Various Oxygen Partial Pressures on Peripheral Vision, Effect of Increased Oxygen Tension on Dark Adaptation, NAEC-ACEL-517, Naval Air Engineering Center, Philadelphia, Pa., Feb. 1964.

11-28. Damato, M. J., Highly, F. M., Hendler, E., et al., Rapid Decompression Hazards after Prolonged Exposure to 50% Oxygen-50% Nitrogen Atmosphere, Aerospace Med., 34: 1037-1040, Nov. 1963.

11-29. Degner, E. A., Ikels, K. G., Allen, T. H., Dissolved Nitrogen and Bends in Oxygen-nitrogen Mixtures during Exercise at Decreased Pressures, Aerospace Med., 36: 418-425, May, 1965.

11-30. Dianov, A. G., The Possibilities of Replacing the Nitrogen in the Air with Helium in Spacecraft Cabins and the Effectiveness of Using a Helium-Oxygen Mixture for Ventilation in Spacesuits, NASA-TT-F-9042, July 1964. (Translation of Kosmicheskiye Issledovaniya, 2 (3): 498-503, 1964).

11-31. DuBois, A. B., Turaids, T., Mammen, R. E., et al., Pulmonary Atelectasis in Subjects Breathing Oxygen at Sea Level or at Simulated Altitude, J. Appl. Physiol., 21 (3): 828-836, May 1966.

11-32. Dunn, H, K., The Calculation of Vowel Resonances on Electrical Vocal Tract, J. Acoust. Soc. Amer., 22: 740-753, 1950.

11-33. Epperson, W. L., Quigley, D. G., Robertson, W. G., et al., Observations on Man in an Oxygen-helium Environment at 380 mm Hg Total Pressure: III. Heat Exchange, Aerospace Med., 37: 457-462, May 1966.

11-34. Faulconer, A., Jr., Ridley, R. W., Continuous Quantitative Analysis of Mixtures of Oxygen, Nitrous Oxide and Ether with and without Nitrogen; Acoustic Gas Analyzer for Mixtures of First Three Gases; Acoustic Gas Analyzer and Beckman Oxygen Analyzer for Mixtures of Four Gases, Anesthes., 11: 265-278, May 1950.

11-35. Featherstone, R. M., Muehlbaecher, C. A., The Current Role of Inert Gases in the Search for Anesthesia Mechanisms, Pharmacol. Rev., 15: 97-121, 1963.

11-36. Gallagher, T. J., Mammen, R. E., Nobrega, F. T., et al., The Effects of Various Oxygen Partial Pressures on Scotopic and Photopic Vision, NAEC-ACEL-530, Naval Air Engineering Center, Philadelphia, Pa., July 1965.

11-37. General Electric Missile and Space Division, Space Station System Simulation, Results of a 4-Man/30-day Mission Simulation Program, GE-64SD679, Philadelphia, Pa., Apr. 23, 1964.

11-38 Gertz, K. H., Loeschcke, H. H., Bestimmung der Diffusions-Koeffizienten von H_2, O_2, N_2, und He in Wasser und Blutserum bei konstant gehaltener Konektion, Z. Naturforsch., 9b (1): 1-9, 1954.

11-39. Glatte, H. V., Giannetta, C. L., Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. III. Renal Response, SAM-TR-66-250, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 559-562, June 1966).

11-40. Golden, R. M., Improving Naturalness and Intelligibility of Helium-Oxygen Speech, Using Vocoder Techniques, J. Acoust. Soc. Amer. 39: 1239(A)-1240, 1966.

11-41. Green, F. H., Psychrometric Data, ARMC-66-537, AiResearch Mfg. Co., Division of Garrett Corp., Los Angeles, Calif., May 15, 1966.

11-42. Hall, A. L., Kelly, H. B., Jr., Exposure of Human Subjects to 100% Oxygen at Simulated 34,000 Foot Altitude for Five Days, NMC-TM-62-7, Naval Missile Center, Point Mugu, Calif., Apr. 1962.

11-43. Hall, A. L., Martin, R. J., Prolonged Exposure in the Navy Full Pressure Suit at Space Equivalent Altitude, Aerospace Med., 31: 116-122, Feb. 1960.

11-44. Hargreaves, J. J., Robertson, W. G., Ulvedal, F., et al., The Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. I. Introduction and General Experimental Design, SAM-TR-66-256, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 552-555, June 1966).

11-45. Heidelbaugh, N. D., Vanderveen, J. E., Klicka, M. V., et al., Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. VIII. Observations on Feeding Bite-size Foods, Aerospace Med., 37: 583-590, June 1966.

11-46. Helvey, W. M., Effects of Prolonged Exposure to Pure Oxygen on Human Performance, RAC-393-1 (ARD 807-701), Republic Aviation Corp., Farmingdale,N. Y., Nov. 1962. (Prepared under Contract NASr-92).

11-47. Hendler, E., Physiological Effects of a Simulated Space Flight Profile, Fed. Proc., 22 (4): 1060-1063, July-Aug. 1963.

11-48. Hendler, E., Physiological Evaluations of Artificial Spacecraft Atmospheres, ASMA-66-19, Aerospace Crew Equipment Laboratory, Naval Air Engineering Center, Philadelphia, Pa., paper presented at 37th Annual Meeting of the Aerospace Medical Association, Las Vegas, Nev., April 18-21, 1966.

11-49. Herlocher, J. E., Quigley, D. G., Behar, V. S., et al., Physiologic Response to Increased Oxygen Partial Pressure. I. Clinical Observations, Aerospace Med., 35: 613-618, July 1964.

11-50. Hiatt, E. P., Weiss, H. S., Biological Effects of Prolonged Exposure of Small Animals to Unusual Gas Environments, NASA-CR-59083, Sept. 1964.

11-51. Holywell, K., Harvey, G., Helium Speech, J. Acoust. Soc. Amer., 36: 210(L)-211, 1964.

11-52. Jacobson, S. L., Engineering of the Sealed Cabin Atmosphere Control System, paper presented at the 30th Annual Meeting of the Aeromedical Association, Los Angeles, Calif., Apr. 27-29, 1959.

11-53. Johnson, A. L., Aerospace Corp., Manager, Life Support Section, Los Angeles, Calif., unpublished data, to be published in the Diluent Selection Study for the MOL Program, 1966.

11-54. Johnson, L. F., Jr., Neville, J. R., Bancroft, R. W., et al., Physical Transducers for Sensing Oxygen, SAM-Review 8-63, School of Aerospace Medicine, Brooks AFB, Texas, Aug. 1963.

11-55. Jones, R. L., Evaluation and Comparison of Three Space Suit Assemblies, NASA-TN-D-3482, July 1966.

11-56. Keating, D. A., Weiswurm, K., Meyer, C. M., et al., Manned Testing of a Semipassive Potassium Superoxide Atmosphere Control System, AMRL-TR-65-194, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Nov. 1965.

11-57. Kellett, G. L., Coburn, K. R., The Effects Upon the Red Blood Cells of Subjects Exposed for a Prolonged Period to 100% Oxygen at 5 psia, ASMA-66-15, Aerospace Crew Equipment Laboratory, Naval Air Engineering Center, Philadelphia, Pa., paper presented at the 37th Annual Meeting of the Aerospace Medical Association, Las Vegas, Nev., Apr. 18-21, 1966.

11-58. Kellett, G. L., Coburn, K. R., Hendler, E., An Investigation of Decompression on Hazards Following Equilibrium in a Simulated Spacecraft Atmosphere of 50% O_2-50% He at 380 mm Hg, NAEC, ACEL-540, Naval Air Engineering Center, Philadelphia, Pa., 1966.

11-59. Kuznetsov, A. G., Agadzhanyan, N. A., Dianov, A. G., et al., Effect on the Body of Prolonged Exposure to Conditions of Artificial Atmosphere, NASA-TT-F-276, 1964. (Translation of Vliyaniye na Organizm Dlitel'Nogo Prebyvaniya v Usloviyakh Iskusstvennoy Atmosfery, presented at XV International Astronautical Congress, Warsaw, Poland, Sept. 7-12, 1964).

11-60. Litton Systems, Inc., Space Sciences Labs., The Litton Extravehicular and Lunar Surface Suit, Pub. No. 4653, Beverly Hills, Calif., Jan 1966.

11-61. MacLean, D. J., Analysis of Speech in a Helium-Oxygen Mixture under Pressure, J. Acoust. Soc. Amer., 39: 1238 (A)-1240, 1966.

11-62. Mammen, R.E., Critz, G. T., Dery, D. W., et al., Effect of Sequential Exposure to Acceleration and the Gaseous Environment of the Space Capsule upon the Physiologic Adaptation of Man, NAEC-ACEL-498, Naval Air Engineering Center, Philadelphia, Pa., June 1963.

11-63. Mason, J. L., Potter, J., AiResearch Mfg. Co., Division of Garrett Corp., Los Angeles, Calif., personal communication of unpublished data, Mar. 1966.

11-64. Mason, J. L., Waggoner, J. N., Ruder, J., The Two-Gas Spacecraft Cabin Atmosphere Engineering Considerations, AirResearch Mfg. Co., Division of Garrett Corp., Los Angeles, California, in Life in a Spacecraft, Proceedings, International Astronautical Congress, 16th, Athens, Greece, Sept. 13-19, 1965, Lunc, M., (ed.), pp. 255-274.

11-65. Matsch, L. C., Associate Technical Director, Linde Division, Union Carbide Corp., Tonawanda, N. Y., personal communication, Mar. 1966.

11-66. Melfi, L. T., Jr., Wood, G. M., Jr., The Use of an Ionization Gage as a Quantitative Analyzer for Bi-Gaseous Mixtures, NASA-TN-D-1597, Dec. 1962.

11-67. Meneely, G. R., Kaltreider, N. L., Volume of Lung Determined by Helium Dilution, Description of Method and Comparison with Other Procedures, J. Clin. Invest., 28: 129-139, Jan. 1949.

11-68. Michel, E. L., Langevin, R. W., Gell, C. F., Effect of Continuous Human Exposure to Oxygen Tension of 418 mm Hg for 168 Hours, Aerospace Med., 31: 138-144, Feb. 1960.

11-69. Mickelson, W. F., Hypes, W. D., Oxygen-Nitrogen Indicator-Controller and Space Cabin Outboard Leak Simulator, AMRL-TDR-64-25, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, June 1964.

11-70. Morgan, T. E., Jr., Ulvedal, F., Cutler, R. G., et al., Effects on Man of Prolonged Exposure to Oxygen at a Total Pressure of 190 mm Hg., Aerospace Med., 34, 589-592, July 1963.

11-71. Morgan, T. E., Jr., Ulvedal, F., Welch, B. E., Observations in the SAM Two-Man Space-Cabin Simulator. II. Biomedical Aspects, Aerospace Med., 32, 591-602, July 1961.

11-72. Moyer, J. E., Farrell, D. G., Lamb, W. L., et al., The Study of Man During a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure, XI. Oral, Cutaneous and Aerosol Bacteriologic Evaluation, SAM-TR-66-244, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 597-600, June 1966).

11-73. National Aeronautics and Space Administration, Mercury Project Summary Including the Results of the Fourth Manned Orbital Flight, Manned Spacecraft Center, Houston, Texas, May 15-16, 1963, NASA-SP-45, 1963.

11-74. Nixon, C. W., Trimboli, F., Speech in an Artificial Atmosphere (44% Oxygen-56% Helium), AMRL-TR-66-165, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Dec. 1966.

11-75. Nobrega, F. T., Turaids, F. T., Gallagher, T. J., Production of Absorptional Atelectasis in High Oxygen Environment at a Simulated Altutude of 27,000 Feet, NAEC-ACEL-528, Naval Air Engineering Center, Philadelphia, Pa., Apr. 1965.

11-76. Perkin-Elmer Corp., A Mass Spectrometer Two-Gas Atmosphere Sensor System, Aerospace Systems, Pomona, Calif., (no date).

11-77 Perkin-Elmer Corp., Two Gas Atmosphere Sensor System, Preliminary Design, Phase IIa Report, Engineering Rep. 8768, Norwalk, Conn., May 1967. (Prepared under Contract NAS1-6467).

11-78. Powell, A., On the Edgetone, J. Acoust. Soc. Amer., 33: 395-409, 1961.

11-79. Reed, A., Evaluation of Gas Composition Detection Methods in Manned Space Vehicles, Rep. ADR-04-06-62.1, Grumman Aircraft Engineering Corp., Bethpage, N. Y., Dec. 1962.

11-80. Richardson, D. L., Research to Advance Extravehicular Protective Technology, AMRL-TR-66-250, Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Apr. 1967.

11-81. Rinfret, A. P., Doebbler, G. F., Physiological and Biochemical Effects and Applications, in Argon, Helium, and the Rare Gases, Cook, G. A., (ed.), Interscience, N. Y., 1961, Vol. II, pp. 727-764.

11-82 Robertson, W. G., Hargreaves, J. J. Herlocher, J. E., et al., Physiologic Response to Increased Oxygen Partial Pressure. II. Respiratory Studies, Aerospace Med., 35: 618-622, July 1964.

11-83. Robertson, W. G., McRae, G. L., The Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. VII. Respiratory Function, SAM-TR-66-257, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 578-582, June 1966).

11-84. Robertson, W. G., Zeft, H. J., Behar, V. S., et al., Observations on Man in an Oxygen-Helium Environment at 380 mm Hg Total Pressure. II. Respiratory, Aerospace Med., 37: 453-456, May 1966.

11-85. Rodgin, D. W., Hartman, B. O., The Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. XIII. Behavior Factors, SAM-TR-66-247, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 605-608, June 1966).

11-86. Roth, E. M., Foundations of Space Biology and Medicine, Monograph #8, Effect on the Organism of the Artificial Gaseous Atmosphere of Spacecraft and Stations, Lovelace Foundation for Medical Education and Research, Albuquerque, N.M., report prepared under Contract NASr-115, submitted to NASA, Office of Space Science and Applications, Washington, D. C., Jan 30, 1968.

11-87. Roth, E. M., Selection of Space-Cabin Atmospheres, Space Science Rev., 6: 452-492, 1967.

11-88. Roth, E. M., Space-Cabin Atmospheres. Part II. Fire and Blast Hazards, NASA-SP-48, 1964.

11-89. Roth, E. M., Space-Cabin Atmospheres. Part III. Physiological Factors of Inert Gases, NASA-SP-117, 1967.

11-90. Roth, E. M., Space-Cabin Atmospheres. Part IV. Engineering Trade-Offs of One-Versus Two-Gas Systems, NASA-SP-118, 1967.

11-91. Rousseau, J., Burris, W. L., Coe, C. S., et al., Atmospheric Control Systems for Space Vehicles, ASD-TDR-62-527, Pt. I, Aeronautical Systems Div., Wright-Patterson AFB, Ohio, Mar. 1963.

11-92. Sergeant, R. L., The Effect of Frequency Passband upon the Intelligibility of Helium-Speech in Noise, SMRL-480, Naval Submarine Medical Research Lab., Groton, Conn., Aug. 1966.

11-93. Sergeant, R. L., Speech During Respiration of a Mixture of Helium and Oxygen, Aerospace Med., 34: 826-829, Sept. 1963.

11-94. Secord, T. C., Bonura, M. S., Life Support Systems Data from Sixty-Two Days of Testing in a Manned Space Laboratory Simulator, in AIAA Fourth Manned Space Flight Meeting, Oct. 11-13, 1965, St. Louis, Missouri, American Institute of Aeronautics and Astronautics, N.Y., 1965, pp. 306-317.

11-95. Speakman, J. D., Physical Analysis of Speech in Helium Environments, Aerospace Med., 39: 48-53, Jan. 1968.

11-96. Srivastava, B. N., Barua, A. K., Thermal Conductivity of Binary Mixtures of Diatomic and Monatomic Gases, J. Chem. Phys., 32: 427-435, Feb. 1960.

11-97. Stanford Research Institute, Menlo Park, Calif., Elastic Orifices for Gas Bearings, NASA-SP-5029, Aug. 1965.

11-98. Steinkamp, G. R., Hawkins, W., et al., Human Experimentation in the Space Cabin Simulator, SAM-59-101, School of Aerospace Medicine, Brooks AFB, Texas, Aug. 1959.

11-99. Sternbergh, S. A., Hickam, W. M., Flight Type Oxygen Partial Pressure Sensor, NASA-CR-534, Aug. 1966.

11-100. Taylor, B. N., Barker, R. S., Analytical Simulation of the Langley Research Center Integrated Life-Support System, Vol. I, NASA-CR-66454, Jan. 1968.

11-101. Tietze, H., Technical Possibilities for the Construction of Light Weight Diving Devices and Artificial Gas Mixtures, in Proceedings of the Conference on Decompression Sickness, Bad Godesberg, Nov. 16-17, 1962, DVL-258, Deutsche Versuchsanstalt fur Luftfahrt E. V., Institut fur Flugmedizin, 1962, pp. 47-57.

11-102. Travis, L. E. (ed.), Handbook of Speech Pathology, Appleton-Century-Crofts, Inc., N. Y., 1957.

11-103. Trout, O. F., Jr., Sealing Manned Spacecraft, Astron. and Aerosp. Engr., 1: 44-46, Aug. 1963.

11-104. Ulvedal, F., Roberts, A. J., Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. VI. Excretion of Steroids and Catecholamines, Aerospace Med., 37: 572-578, June 1966.

11-105. Vance, R. W. (ed.), Cryogenic Technology. John Wiley & Sons, N. Y., 1963.

11-106. Van Den Berg, Jw., Calculations on a Model of the Vocal Tract for i (Meat) and on the Larynx, J. Acoust. Soc. Amer., 27: 332-338, 1955.

11-107. Vanderveen, J. E., Heidelbaugh, N. D., O'Hara, M. J., The Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. IX. Nutritional Evaluation of Feeding Bitsize Foods, SAM-TR-66-243, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 591-594, June 1966).

11-108 Van Slyke, D. D., Dillon, R. T., Margaria, R., Studies of Gas and Electrolyte Equilibria in Blood. 18. Solubility and Physical State of Atmospheric Nitrogen in Blood Cells and Plasma, J. Biol. Chem., 105: 571--596, 1934.

11-109. Warner, H., Oxygen Partial Pressure Sensor, Med. Electron. Biol. Engng., 1: 79-84, 1963.

11-110. Wathen-Dunn, W., Limitations of Speech at High Pressures in a Helium Environment, Air Force Cambridge Research Labs., Bedford, Mass., in: Third Symposium on Underwater Physiology, Washington, D. C., March 23-25, 1966, Lambertson, C. J. (ed.), Williams and Wilkins Co., Baltimore, 1967, pp. 128-137.

11-111 Welch, B. E., Chief, Environmental Systems Branch, School of Aerospace Medicine, Brooks AFB, Texas, personal communication, Mar. 1966.

11-112. Welch, B. E., Morgan, T. E. Jr., Ulvedal, F., et al., Observations in the SAM Two-man Space Cabin Simulator. I. Logistics Aspects, Aerospace Med., 32: 583-590, July 1961.

11-113. Welch, B. E., Robertson, W. G., Glatte, H. V., et al., The Study of Man during a 56-Day exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure, School of Aerospace Medicine, Brooks AFB, Texas, paper presented at the 37th Annual Meeting of the Aerospace Medical Association, Apr. 18-21, 1966, Las Vegas, Nev.

11-114. Wilhite, W. F., The Development of the Surveyor Gas Chromatograph, JPL-TR-32-425, California Institute of Technology, Jet Propulsion Lab., Pasadena, Calif., May 1963.

11-115. Wilhite, W. F., Burnell, M. R., Lunar Gas Chromatograph, ISA Journal, 10: 53-59, Sept. 1963.

11-116. Wortman, J. J., A Feasibility Study of a Thin Film Oxygen Partial Pressure Sensor, NASA-CR-66084, Jan.1966.

11-117. Wright, R. A., Kreglow, E. S., Weiss, H. S., Effects of Changing Environmental Factors in Embryonic Development in a Helium-Oxygen Atmosphere, paper presented at the 37th Annual Meeting, Aerospace Medical Association, Apr. 18-21, 1966, Las Vegas, Nev.

11-118. Wright, R. A., Lessler, M. A., Weiss, H. S., Metabolism and X-ray Sensitivity of Chick Embryos Incubated in a Helium-Oxygen Atmosphere, Aerospace Med., 36: 311-314, Apr. 1965.

11-119. Young, J. A., Manheim, A., Flinn, R. A., Preliminary Observations of the Respiratory Effects of Neon, Guthrie Clin. Bull., 33: 30-38, 1963.

11-120. Zalusky, R., Ulvedal, F., Herlocher, J. E., et al., Physiologic Response to Increased Oxygen Partial Pressure. III. Hematopoiesis, Aerospace Med., 35: 622-626, July 1964.

11-121. Zeft, H. J., Behar, V. S., Quigley, D. G., et al., Observations on Man in an Oxygen-Helium Environment at 380 mm Hg Total Pressure, I. Clinical, Aerospace Med., 37: 449-453, May 1966.

11-122. Zeft, H. J., Krasnogor, L. J., Motsay, G. J., et al., The Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. XII. Clinical Observations, SAM-TR-66-255, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 601-604, June 1966).

11-123. Zeft, H. J., Robertson, W. G., Welch, B.E., The Study of Man during a 56-Day Exposure to an Oxygen-Helium Atmosphere at 258 mm Hg Total Pressure. V. Exercise Performance and Cardiovascular Response, SAM-TR-66-252, School of Aerospace Medicine, Brooks AFB, Texas, June 1966. (Also in: Aerospace Med., 37: 566-571, June 1966).