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HUMAN COMPATIBILITY TESTING OF A 2-MAN MOLECULAR SIEVE OXYGEN GENERATOR

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This report describes a series of human compatibility tests conducted to man-rate a 2-man molecular sieve oxygen generating system prior to aircraft flight test in the U.S. Navy EA-6B aircraft. The protocol included ground-level evaluations and chamber flights up to 13.4 km (44,000 ft.) altitude, simulating the operating envelope of the EA-6B. It was concluded that the molecular sieve generating unit provided adequate oxygen under all anticipated flight conditions. It was recommended, however, that the flight test program incorporate an improved oxygen regulator to enhance system performance.

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HUMAN COMPATIBILITY TESTING OF A 2-MAN MOLECULAR SIEVE OXYGEN GENERATOR

INTRODUCTION

Air enrichment via molecular sieve is one of several candidate onboard oxygen generation systems under joint Navy-Air Force development for application in tactical aircraft (8). Compared to other systems for in-flight generation of oxygen, the molecular sieve offers the advantage of low aircraft penalty for weight and power, but the disadvantage of producing a breathing gas which contains less than 100% oxygen (3, 5, 7). The latter results from a unique feature of air fractionation by molecular sieve in that oxygen can be separated from nitrogen but not from argon. The first generation of molecular sieve oxygen systems produced a product containing 50% to 70% oxygen. However, more recent developments in molecular sieve bed design have improved the separation efficiency to produce a breathing gas containing approximately 95% oxygen - 5% argon.

To demonstrate feasibility of onboard generation, the Naval Air Development Center, Warminster, Pennsylvania, in 1976 developed a prototype 2-man molecular sieve oxygen generating system for preliminary flight test in the U.S. Navy EA-6B "Prowler" aircraft. The 2-man system was designed and fabricated by Bendix Corporation, Instruments and Life Support Division, Davenport, Iowa. The unit has been previously described by Miller et al. (5), who conducted extensive tests to determine the composition of the product breathing gas as a function of flow, inlet pressure, and cabin altitude.

This report describes a series of human compatibility tests conducted to man-rate the 2-man molecular sieve system prior to aircraft flight test. The evaluation program was specifically designed to determine human compatibility of the combined subsystems for generation and delivery of breathing gas to the crewmember under anticipated flight conditions. Independent test parameters included cabin and exhaust altitude, air supply pressure to the molecular sieve generating unit, multiple test subjects, and variation in subject ventilation (workload). Dependent parameters evaluated were breathing gas composition (oxygen, nitrogen, argon, and carbon dioxide), mask suction pressure (breathing resistance), and subject fatigue.

METHODS

Test Subjects

The test program was designed to conduct human compatibility evaluation (man-rating) of the 2-man molecular sieve oxygen generating unit under simulated flight conditions. The test protocol included 5 ground-level evaluations and 14 flight profiles using a total of 14 male volunteer test subjects. Each test involved two subjects and was conducted under one of three workloads (minute volumes). For purposes of this study, a resting (or zero) workload corresponded to a minute volume of 5 to 15 LPM (BTPS), light workload to a minute volume ($\dot{V}_E$) of 15 to 25 LPM, and moderate workload to a minute volume of 25 to 40 LPM (2). The elevated minute volumes were induced by exercising on a bicycle ergometer. The $\dot{V}_E$ - exercise relationship for each subject was determined individually prior to the test program. Table 1 lists the vital statistics of the test subjects as well as their minute volumes at each workload.

TABLE 1. VITAL STATISTICS OF THE SUBJECT PANEL

Subject	Age (yr)	Weight (kg)	Height (cm)	Minute volume (liters) At rest	Light workload	Moderate workload
A	26	81.8	185.4	-	-	-
B	32	75.0	188.0	6.2	19.9	36.5
C	28	71.4	173.7	-	23.8	33.8
D	22	59.1	177.8	6.7	15.0	34.3
E	37	72.7	175.3	7.7	16.9	33.2
F	22	61.4	170.2	7.7	21.8	38.5
G	34	70.5	173.7	-	19.4	36.2
H	42	77.3	172.7	-	-	-
I	24	88.6	188.0	-	25.4	33.5
J	25	77.3	188.0	9.3	19.3	31.6
K	30	63.7	167.7	8.8	15.6	30.8
L	31	87.3	180.3	-	22.4	35.4
M	22	84.1	188.0	6.5	18.7	33.2
N	31	103.2	198.1	7.6	-	-
Subject mean	29.0	76.7	180.5			
Rated AF mean (2)	30.0	78.9	177.0			

Experimental Setup

The experimental setup for the manned test runs is shown schematically in Figure 1. The molecular sieve generating unit was positioned adjacent to chamber 1, which received the nitrogen-rich exhaust gas at simulated aircraft altitude. The test subjects were housed in chamber 2 (Figure 2), which was used to simulate the aircraft cabin altitude for the manned test runs. The product gas from the molecular sieve was piped to oxygen regulators inside chamber 2 through approximately 24 meters (80 Ft) of 8-mm (5/16 inch) O.D. copper tube to simulate aircraft

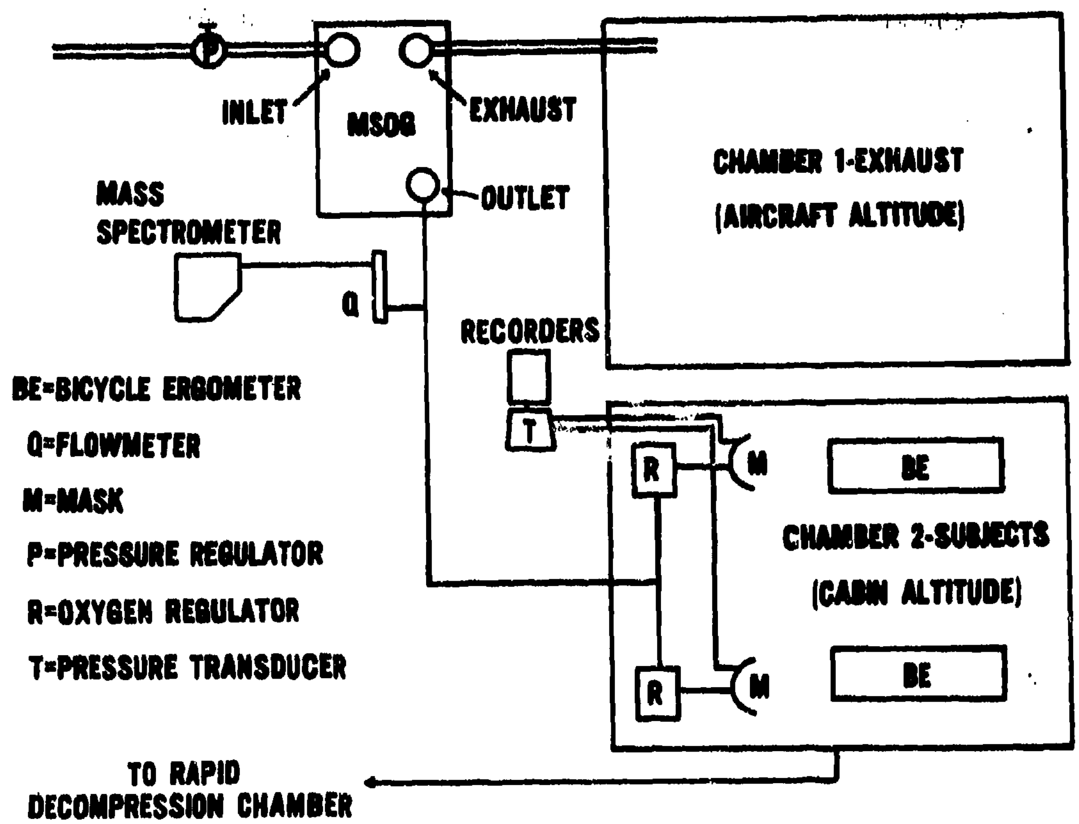

Figure 1. Schematic of experimental setup for manned chamber runs.

configuration. The total reservoir capacity between the molecular sieve unit and the regulators was 2.2 liters, which was made up of 1.0 liter in the unit itself and 1.2 liters in the connecting lines. The air supply to the sieve unit was standard 10.2 ATA (150 psig), filtered, instrument air from a water-sealed compressor, dried to -14°C, and controlled to the desired inlet pressure by a diaphragm regulator located immediately upstream of the molecular sieve unit.

Inside the chamber, the product gas was delivered to each test subject through a modified CRU-68 oxygen regulator, CRU-60/P connector, and MBU-5/P oxygen mask. The modification to the CRU-68 regulator involved adjustment of the diaphragm to allow demand operation at very low inlet supply pressures (down to approximately 0.07 ATA (1 psig)). In all manned tests, the regulators were set in the 100% delivery mode. Prior to the test program the regulators were tested to determine their positive pressure delivery schedule under static conditions using the USAFSAM oxygen regulator test stand (10).

Figure 2. Experimental setup showing subject exercising on bicycle ergometer while breathing on molecular sieve generator.

Product gas composition was monitored in each test by a four-channel respiratory mass spectrometer (Perkin-Elmer Model MGA-1100). The monitored gases were: oxygen (0-100%), nitrogen (0-100%), carbon dioxide (0-5%), and argon (0-10%). The concentration of each gas was continuously recorded on dual-channel strip chart recorders.

During portions of the test program, breathing gas pressure in the facemask was also measured to determine mask suction pressure. For these tests the MBU-5/P oxygen mask was modified to incorporate a pressure transducer (Viatran Model 220-24) into the oronasal cavity. The output from the transducer was continuously recorded on strip charts (Brush Model 220), which were later examined to determine average suction pressures.

During all simulated flight tests, the altitude chambers were manned with inside and outside observers. The chambers were also equipped with alternate oxygen supply systems for subject use in the event of test equipment failure.

RESULTS AND DISCUSSION

Regulator Tests

The outlet pressure characteristics of the two modified CRU-68 pressure demand regulators are shown in Table 2. This data was obtained under static flow conditions in the USAFSAM regulator test stand and indicates the delivery pressure of each regulator from 8.5 km (28,000 ft), where positive pressure began, to 14.3 km (47,000 ft). At all altitude settings above 8.5 km (28,000 ft), the outlet pressure of the modified regulators was greater than that of standard CRU-68s (6), which was due in part to the diaphragm adjustment necessary to maintain demand flow at very low inlet pressures. According to Table III of MIL-R-83178 the maximum allowable outlet pressure for pressure-demand oxygen regulators at 13.1 km (43,000 ft) is 19.0 mm Hg. When the inlet pressure to the molecular sieve was set to its maximum value of 5.1 ATA (60 psig), the outlet pressure of one of the modified CRU-68 regulators was in excess of 50 mm Hg which was considered somewhat hazardous (1) and greatly in excess of that required to maintain an acceptable inspired oxygen tension with a breathing gas containing 95% oxygen. Hence, for all of the manned testing involving altitude excursions greater than 8.5 km (28,000 ft), the outlet pressure to the molecular sieve unit was set at 3.7 ATA (40 psig) or lower.

Ground-Level Testing

Preliminary evaluations at ground level were designed to perfect measuring techniques and to debug instrumentation, as well as to provide an indication of the molecular sieve performance under dynamic (manned) breathing conditions. Five ground-level tests were made, each with two subjects. The first two tests were conducted with the subjects at rest. Inlet pressure to the molecular sieve unit was initially set at 5.1 ATA (60 psig) and progressively reduced to 3.7 ATA (40 psig), 2.7 ATA (25 psig), 2.0 ATA (15 psig), and finally to 1.5 ATA (8 psig). At each inlet pressure, the product gas composition was recorded for a 6-minute steady state period. The third test was conducted with two subjects at light workload, and the final two tests with two subjects at moderate workload. In each workload test, the inlet pressure to the molecular sieve was initially set at 5.1 ATA (60 psig) and progressively reduced to as low a setting as the subjects could tolerate due to breathing resistance.

The results of the ground-level tests are shown in Table 3. In every test the oxygen concentration showed a progressive reduction with decreasing inlet pressure to the molecular sieve. With subjects at rest the oxygen concentration ranged from 93% at 5.1 ATA (60 psig) to 27% at 1.5 ATA (8 psig) inlet pressure. The pattern was exacerbated by subject workload, which served to increase mass flow demand on the system. At moderate workloads the subjects were unable to tolerate breathing resistance associated with inlet pressures less than about 3.7 ATA (40 psig).

TABLE 2. DELIVERY PRESSURE OF MODIFIED CRU-68 OXYGEN REGULATORS

Inlet pressure ATA (psig)	Altitude thousands km (kft)	Delivery pressure (mm Hg) SN 804419 0 Flow	SN 804419 20 LPM	SN 505504 0 Flow	SN 505504 20 LPM
1.7 (10)	8.5 (28)	4.2	2.1	3.1	2.5
	9.1 (30)	3.6	2.3	6.9	6.7
	9.8 (32)	3.9	2.4	6.7	6.4
	10.4 (34)	4.1	2.7	8.3	6.8
	11.0 (36)	4.6	4.0	7.9	5.8
	11.6 (38)	10.9	10.6	9.9	6.9
	12.2 (40)	17.6	16.2	14.6	13.3
	13.1 (43)	24.8	23.3	22.9	21.3
	13.7 (45)	30.6	26.3	27.2	25.7
2.7 (25)	8.5 (28)	1.6	2.0	5.8	4.1
	9.1 (30)	2.6	2.1	7.1	6.6
	9.8 (32)	3.1	1.9	7.4	7.1
	10.4 (34)	3.1	2.0	5.9	5.9
	11.0 (36)	5.0	3.1	7.8	6.6
	11.6 (38)	12.7	10.8	11.2	8.9
	12.2 (40)	17.5	16.7	16.8	16.2
	13.1 (43)	26.9	22.8	23.6	23.0
	13.7 (45)	31.6	27.5	28.4	26.8
3.7 (40)	8.5 (28)	3.0	2.1	6.2	4.8
	9.1 (30)	3.0	1.9	6.6	5.5
	9.8 (32)	3.2	2.2	5.8	5.0
	10.4 (34)	3.6	2.5	9.0	7.0
	11.0 (36)	5.5	5.2	9.4	7.8
	11.6 (38)	13.4	13.1	13.0	10.9
	12.2 (40)	19.7	16.8	19.1	16.1
	13.1 (43)	24.8	24.3	25.3	24.4
	13.7 (45)	32.5	28.1	30.4	28.8
5.1 (60)	8.5 (28)	54.7	3.2	38.3	8.7
	9.1 (30)	55.4	2.3	38.9	9.0
	9.8 (32)	55.7	3.5	39.0	9.3
	10.4 (34)	56.1	3.8	39.0	10.0
	11.0 (36)	56.2	6.4	39.2	10.9
	11.6 (38)	56.5	12.6	39.4	16.9
	12.2 (40)	57.0	20.4	39.8	22.4
	13.1 (43)	57.2	24.8	40.0	30.3
	13.7 (45)	57.3	28.6	40.1	30.3

TABLE 3. GROUND-LEVEL TESTING

Run	Subjects	Inlet pressure ATA (psig)	Exercise level	O_2 %	N_2 %	Ar %	CO_2 %
1	D,F	5.1 (60)	0	92.4	3.3	4.4	0.0
		3.7 (40)	0	91.8	3.8	4.4	0.0
		2.7 (25)	0	82.3	13.7	3.9	0.0
		2.0 (15)	0	56.3	41.0	2.7	0.0
		1.5 (8)	0	35.0	63.0	2.0	0.0
2	K,L	5.1 (60)	0	93.0	2.4	4.5	0.0
		3.7 (40)	0	92.8	2.8	4.4	0.0
		2.7 (25)	0	83.5	10.5	4.0	0.0
		2.0 (15)	0	50.6	47.0	2.4	0.0
		1.5 (8)	0	27.6	71.0	1.4	0.0
3	D,F	5.1 (60)	L	58.2	39.0	2.8	0.0
		3.7 (40)	L	51.5	46.0	2.5	0.0
		2.7 (25)	L	42.0	56.0	2.0	0.0
		2.0 (15)	L	35.2	63.0	1.7	0.0
4	D,F	5.1 (60)	M	45.9	52.0	2.1	0.0
		3.7 (40)	M	42.0	56.0	2.0	0.0
5	K,M	5.1 (60)	M	50.5	47.0	2.5	0.0
		3.7 (40)	M	46.8	51.0	2.2	0.0

[a]Exercise level: Zero signifies subjects at rest, L = light, and M = moderate.

Altitude Testing - No Exercise

The altitude-time profiles for the three, no-exercise flights are shown in Figure 3. These profiles were selected to simulate the pressurization schedule and mission envelope of the EA-6B aircraft, which is scheduled to be the initial test bed for the molecular sieve oxygen generator system. Profile I was designed to cover the operating envelope for the EA-6B aircraft up to FL-440 with no programmed incident. Profile II was designed as a FL-250 mission with a midpoint decompression (60-, 10-, and 1-sec duration), and mission-completion requirement at FL-250. Profile III was a high-altitude flight (FL-440) with a 10-second midpoint decompression, followed by immediate descent to and mission completion at FL-250.

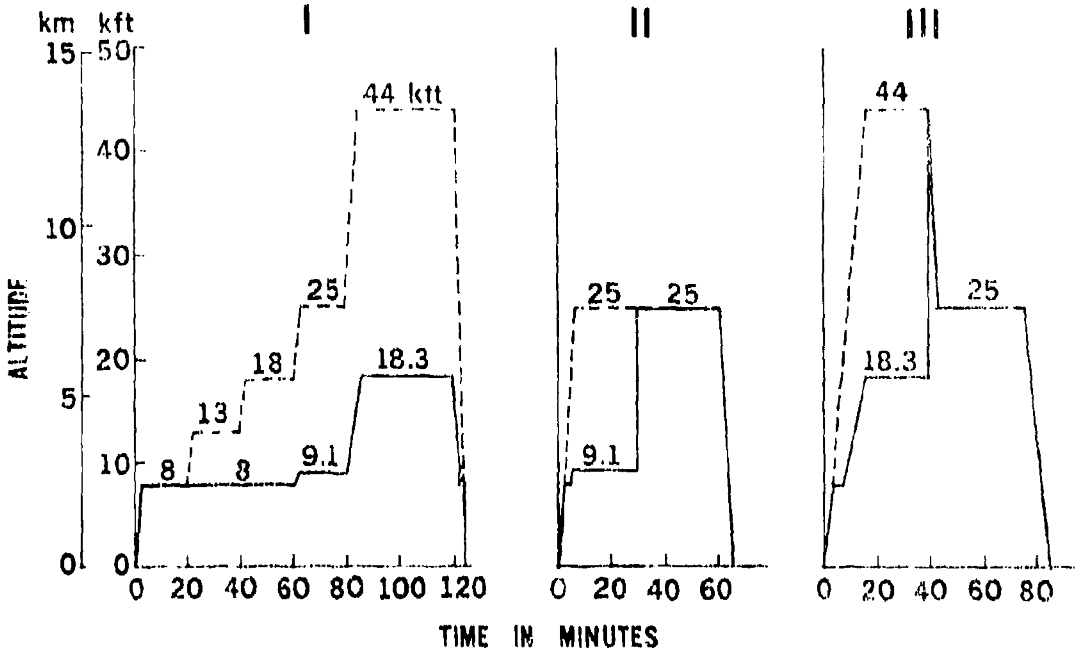

Figure 3. Altitude-time profiles for the three no-exercise manned test flights. Solid line indicates cabin altitude; dashed line, exhaust (aircraft) altitude. Profile II was run three times with decompression times of 60, 10, and 1 second. Decompression in profile III was 10-second duration.

Profile I was run once with two subjects. The group of three Profile II tests (60-, 10-, and 1-sec rapid decompression) was run twice; first with 30 minutes of prebreathing (at ground level on product gas from the molecular sieve), and secondly with no prebreathing. Profile III was run three times; the first flight with 30 minutes of ground-level prebreathing, and the final two flights with no prebreathing. Throughout the profile I, II, and III flights, the inlet pressure to the molecular sieve generator was limited at 3.7 ATA (40 psig).

The results of the resting altitude (decompression) tests are shown in Table 4. The Profile I test was completed without incident; oxygen concentration remained essentially constant at about 95%. The Profile II tests with a midpoint decompression from 2.8 km to 7.6 km (9,100 ft to 25,000 ft) were also largely routine; oxygen concentration varied from 90% to 95% which was due in part to subject variation in ventilation, and in part to such factors as mask fit, vocal activity, and

TABLE 4. ALTITUDE TESTING - NO EXERCISE

Flight	Profile	Subjects	Product gas composition % Oxygen Max/min	Argon Max/min
1	I	B,G	94.0/94.8	5.0/4.8
2[a]	IIA (60 sec RD)	I,L	94.8/90.0	5.2/4.3
3[a]	IIB (10 sec RD)	A,H	94.8/94.3	5.2/5.2
4[a]	IIC (1 sec RD)	C,G	94.8/94.0	5.2/6.0
5	IIA (60 sec RD)	I,L	95.0/93.5	5.0/4.6
6	IIB (10 sec RD)	A,N	95.0/94.0	5.0/4.6
7	IIC (1 sec RD)	C,G	94.8/93.6	5.2/4.6
8[a]	III	C,J	94.8/92.0[b]	-
9	III	C,J	94.7/72.0[b,c]	-
10	III	C,J	94.9/93.9[b]	-

[a]Flight preceded by 30-minute prebreathing period at ground level on the molecular sieve generator.

[b]Oxygen measurements made by electrochemical oxygen analyzer (Beckman Model OM-11). Argon measurements not made.

[c]Subjects held at 44,000 ft for approximately 70 sec due to malfunction in chamber-connecting valve. Flight was terminated.

physical movement. The only unscheduled incident in the test program occurred during the second flight of Profile III when a valve connecting the subject chamber to a vacuum chamber stuck in the open position. Following the programmed decompression, the subjects remained at FL-440 for approximately 70 seconds while the problem was diagnosed and rectified. During this period, the oxygen concentration dropped to about 72% which was attributed, in part, to increased ventilation caused by subject apprehension, and, in part to increased mask blowby from the high regulator outlet pressure. This flight was terminated following the malfunction, and the profile was repeated (Flight 10) without incident. With the exception of the incident, oxygen concentration remained in the range from 92% to 95%.

Altitude Tests - With Exercise

The final series of manned altitude tests were designed to evaluate the effect of inlet pressure to the molecular sieve generating unit on product gas composition as well as on mask suction pressure (breathing gas availability). Four flights were made (Table 5), each with two subjects initially at rest, followed by up to 7-minute periods of exercise on the bicycle ergometer at light and moderate workloads.

TABLE 5. EXPERIMENTAL PARAMETERS FOR ALTITUDE TESTING WITH EXERCISE

Flight	Altitude Cabin km (kft)	Altitude Exhaust km (kft)	Exercise level[a] O-L-M
1	1.5 (5)	1.5 (5)	O-L-M
2	2.4 (8)	2.4 (8)	O-L-M
3	2.4 (8)	3.7 (12)	O-L-M
4	2.4 (8)	6.1 (20)	O-L-M

[a]Exercise level: Zero signifies subject at rest, L = light, and M = moderate.

For these tests, the inlet pressure to the molecular sieve unit was initially set at 5.1 ATA (60 psig) and progressively decreased to 3.7, 2.7, 2.4, 2.0 ATA, and in some experiments to 1.5 ATA (8 psig). At each inlet pressure and workload setting, the product gas composition was recorded, as was the mask suction pressure for the two subjects. The lowest inlet pressure setting in any one test was largely dictated by mask suction pressure. On several occasions, particularly at moderate workload, the subject(s) indicated a desire to terminate the run prematurely because of fatigue induced, at least in part, by the high breathing resistance.

The results of the altitude tests with light and moderate exercise are shown in Tables 6 and 7, respectively. With the subjects at rest, the concentration of molecular sieve breathing gas remained essentially constant in the range from 94% to 95% oxygen, 4% to 6% argon, and was largely independent of either inlet pressure or altitude (cabin and/or exhaust). With the subjects at exercise, the oxygen concentration exhibited some decay with time, which was intensified with decreasing inlet pressure. In general, the oxygen concentration was greater at higher cabin altitude, and had less decay in those runs where exhaust altitude was greater than cabin altitude. With the subjects at light exercise, the product gas concentration after 5 to 7 minutes was in the range from 62% to 87% oxygen, 3% to 6% argon, and 7% to 35% nitrogen. After 3 to 5 minutes of moderate exercise, the product gas ranged from 65% to 92% oxygen, 3% to 6% argon, and 2% to 32% nitrogen. It should be noted, however, that even the lowest concentration of oxygen (62%) was well above the 24% minimum required by MIL-R-83178 for hypoxia protection at 2.4-km (8000-ft) cabin altitude.

TABLE 6. ALTITUDE TESTING, LIGHT WORKLOAD

Altitude Cabin km (kft)	Altitude Exhaust km (kft)	Inlet pressure ATA (psig)	Subjects	Time min	Suction pressure mm Hg	Concentration Avg O_2 %	Concentration Avg Ar %
1.5 (5)	1.5 (5)	5.1 (60)	I/B	1	2.9/3.5	93.8	4.5
				2	3.2/3.6	93.2	4.4
				3	3.5/3.8	91.1	4.2
				4	4.2/3.7	87.0	4.0
				5	4.4/3.9	82.8	3.8
				6	4.6/4.1	80.4	3.7
				7	4.2/4.3	78.9	3.6
		3.7 (40)	I/B	1	3.6/3.2	94.2	5.0
				2	4.0/3.3	94.6	4.5
				3	4.2/3.4	91.0	4.1
				4	4.1/3.7	83.5	3.8
				5	4.2/3.3	76.8	3.4
				6	4.0/3.2	73.3	3.3
				7	3.9/3.6	72.2	3.3
		2.7 (25)	I/B	1	5.9/7.0	94.2	5.7
				2	15.8/23.0	95.0	4.8
				3	17.1/21.6	92.4	4.2
		2.7 (25)[a]		1	18.4/18.2	81.3	3.8
				2	21.6/20.8	79.3	3.7
		2.4 (20)	G/C	1	6.0/10.0	92.9	6.0
				2	5.8/30.4	94.2	5.2
				3	5.5/29.4	94.8	4.5
2.4 (8)	2.4 (8)	5.1 (60)	J/L	1	1.6/5.3	93.8	4.8
				2	2.1/6.1	93.8	4.7
				3	2.3/4.6	93.4	4.6
				4	2.4/4.7	92.3	4.4
				5	2.6/4.9	91.1	4.4
				6	1.9/4.6	90.5	4.3
		3.7 (40)	J/L	1	1.6/4.71	93.9	4.9
				2	2.1/4.3	94.1	5.0
				3	2.1/4.9	93.9	4.6
				4	2.0/5.2	92.8	4.4
				5	2.0/5.0	91.9	4.4
				6	2.2/5.5	91.0	4.4
		2.7 (25)	J/L	1	1.9/4.8	93.8	6.0
				2	2.7/5.0	94.2	4.9
				3	3.2/7.7	91.9	4.4
				4	3.0/12.7	86.0	4.1
				5	2.5/10.6	79.2	3.8
				6	2.5/12.1	75.5	3.6

TABLE 6. (Continued)

Altitude Cabin km (kft)	Altitude Exhaust km (kft)	Inlet pressure ATA (psig)	Subjects	Time min	Suction pressure mm Hg	Concentration Avg O_2 %	Concentration Avg Ar %
2.4 (8)	2.4 (8)	2.7 (25)[a]	J/L	1	1.8/4.1	94.0	5.7
				2	2.6/3.8	94.4	4.8
				3	2.2/5.0	92.9	4.4
				4	2.1/5.9	88.4	4.2
				5	4.3/5.4	82.5	3.9
				6	2.7/4.8	78.6	3.8
2.4 (8)	3.6 (12)	5.1 (60)	G/C	1	3.8/2.0	94.2	4.8
				2	4.0/2.0	94.4	4.8
				3	4.0/2.8	94.1	4.7
				4	4.0/2.8	93.1	4.5
				5	3.8/3.0	91.5	4.4
				6	4.0/3.5	90.4	4.3
		3.7 (40)	G/C	1	3.4/2.0	92.2	4.2
				2	3.5/2.6	94.0	5.4
				3	3.7/3.0	94.4	4.7
				4	4.0/3.0	93.3	4.4
				5	4.0/3.0	91.1	4.3
				6	4.0/3.0	89.3	4.2
		2.7 (25)	G/C	1	3.0/2.6	88.3	4.6
				2	3.3/3.0	92.7	5.5
				3	4.0/3.0	94.6	4.9
				4	4.0/2.7	92.0	4.4
				5	4.0/3.2	85.8	4.0
				6	4.0/3.0	80.2	3.8
		2.4 (20)	G/C	1	3.8/2.6	80.8	4.2
				2	3.9/3.3	94.4	5.0
				3	3.8/5.0	88.6	4.2
				4	4.3/5.1	74.8	3.6
				5	4.0/5.9	67.8	3.3
				6	3.7/4.9	67.4	3.2
		2.0 (15)	G/C	1	2.9/6.0	93.7	5.6
				2	4.3/15.7	93.4	4.6
				3	4.7/13.6	81.1	3.9
				4	4.4/13.3	66.5	3.3
				5	4.4/19.0	64.1	3.1
				6	4.0/21.7	62.2	3.1
		1.5 (8)	G/C	1	6.3/9.9	90.4	5.0
				2	8.1/30.0	93.3	4.3
				3	12.7/44.6	82.4	3.8
				4	14.9/46.3	66.9	3.3

TABLE 6. (Continued)

Altitude		Inlet			Suction	Concentration	
Cabin km (kft)	Exhaust km (kft)	pressure ATA (psig)	Subjects	Time min	pressure mm Hg	Avg O_2 %	Avg Ar %
2.4 (8)	6.1 (20)	5.1 (60)	J/I	1	2.0/4.0	94.3	4.9
				2	2.8/4.2	94.4	4.8
				3	2.5/4.2	94.0	4.6
				4	2.4/4.3	93.2	4.5
				5	2.4/4.0	92.7	4.4
				6	3.1/4.4	92.1	4.4
		3.7 (40)	J/I	1	2.3/4.0	89.3	4.4
				2	2.6/4.1	93.5	5.2
				3	2.7/4.1	94.3	4.8
				4	2.4/4.0	93.6	4.5
				5	2.3/4.0	92.3	4.4
				6	2.3/4.0	91.1	4.3
		2.7 (25)	J/I	1	2.6/5.0	94.5	4.7
				2	3.4/5.4	94.1	4.5
				3	2.9/5.7	92.5	4.4
				4	2.6/5.4	89.8	4.3
				5	3.3/6.3	88.0	4.2
				6	2.4/7.0	87.1	4.2
		2.0 (15)	J/I	1	4.8/9.4	93.7	5.4
				2	8.0/10.5	94.8	4.7
				3	12.8/14.5	93.8	4.4
				4	13.4/18.3	90.6	4.3
				5	12.4/19.1	88.2	4.2
				6	11.1/21.6	86.8	4.2

[a] Switched O_2 regulators

TABLE 7. ALTITUDE TESTING, MODERATE WORKLOAD

Altitude Cabin km (kft)	Altitude Exhaust km (kft)	Inlet pressure ATA (psig)	Subjects	Time min	Suction pressure mm Hg	Concentration Avg O_2 %	Concentration Avg Ar %
1.5 (5)	1.5 (5)	5.1 (60)	I/B	1	4.1/4.0	94.7	5.4
				2	4.9/4.1	93.6	4.5
				3	5.4/4.7	86.4	4.0
				4	5.3/4.5	77.1	3.6
				5	5.4/4.6	72.5	3.3
				6	5.7/4.75	72.2	3.3
		3.7 (40)	I/B	1	4.1/4.7	93.8	5.1
				2	5.0/4.7	94.6	4.8
				3	5.4/5.0	89.6	4.2
				4	5.6/5.8	78.1	3.6
				5	5.4/5.1	70.6	3.3
		3.7 (40)	K/J	1	4.1/3.3	94.5	4.8
				2	5.6/4.0	94.1	4.6
				3	5.6/4.0	90.8	4.2
				4	5.9/5.0	80.2	3.5
				5	6.3/5.0	68.2	3.2
				6	5.9/5.0	64.8	3.1
		2.4 (20)	I/B	1	5.5/5.0	94.7	5.2
				2	17.6/6.3	95.0	4.6
				3	19.0/14.0	93.3	4.2
		2.4 (20)	K/J	1	4.7/3.4	80.0	3.9
				2	18.1/28.4	79.5	3.9
2.4 (8)	2.4 (8)	5.1 (60)	J/L	1	2.0/4.3	94.0	5.0
				2	2.2/4.0	94.0	4.8
				3	2.5/4.3	93.6	4.6
				4	2.8/4.3	91.6	4.3
				5	3.0/4.7	86.6	4.0
				6	2.9/4.5	81.3	3.8
		3.7 (40)	J/L	1	2.0/4.3	93.3	5.4
				2	2.6/4.7	93.9	4.7
				3	2.5/4.6	89.4	4.2
				4	2.8/5.0	83.3	4.0
				5	3.2/5.8	77.1	3.7
				6	2.8/4.9	74.6	3.5
		2.7 (25)	J/L	1	2.6/4.2	90.3	5.2
				2	2.6/5.7	94.3	5.1
				3	3.4/12.3	90.6	4.4
				4	3.9/31.7	81.0	3.9
				5	4.8/28.5	72.9	3.5

TABLE 7. (Continued)

Altitude: Cabin km (kft)	Altitude: Exhaust km (kft)	Inlet pressure ATA (psig)	Subjects	Time min	Suction pressure mm Hg	Concentration: Avg O_2 %	Concentration: Avg Ar %
2.4 (8)	2.4 (8)	2.7 (25)[a]	J/L	1	2.4/3.7	93.6	5.4
				2	3.5/4.6	94.1	4.7
				3	8.3/5.3	89.9	4.2
				4[b]	4.6/4.6	82.0	3.9
				5[b]	4.9/5.6	76.0	3.6
2.4 (8)	3.6 (12)	5.1 (60)	G/C	1	3.0/1.6	94.2	5.4
				2	3.8/2.0	94.3	5.1
				3	4.7/1.8	93.4	4.6
				4	4.7/2.9	89.3	4.3
				5	4.1/2.6	82.8	3.9
				6	4.3/2.4	85.5	3.8
		3.7 (40)	G/C	1	5.2/1.2	87.4	4.9
				2	5.5/2.0	93.6	5.2
				3	4.8/1.9	91.9	4.4
				4	5.3/2.0	85.3	4.0
				5	6.1/3.2	82.1	3.8
				6	6.0/2.5	86.1	3.6
		3.7 (40)	G/C	1	2.9/2.0	94.2	4.9
				2	3.5/2.5	94.2	4.8
				3	5.1/2.6	93.9	4.6
				4	6.4/2.6	92.1	4.3
				5	7.0/2.2	87.9	4.1
				6	6.8/2.9	85.7	4.0
		2.7 (25)	G/C	1	4.2/1.8	92.9	5.6
				2	4.5/3.3	94.3	4.9
				3	5.7/2.6	84.6	4.1
				4	10.4/2.5	69.3	3.4
				5	10.3/5.1	62.9	3.1
				6	11.3/4.2	63.3	3.0
		2.4 (20)	G/C	1	7.9/8.3	85.1	4.2
				2	14.8/22.1	91.6	5.4
				3	17.6/28.3	94.7	5.1
2.4 (8)	6.1 (20)	3.7 (40)	J/I	1	3.1/4.0	94.4	5.3
				2	4.3/3.9	94.4	4.8
				3	4.6/4.3	93.0	4.5
				4	5.1/4.4	89.6	4.2
				5	5.1/4.4	86.5	4.1
				6	5.4/4.6	83.2	3.9

TABLE 7. (Continued)

Altitude		Inlet pressure		Time	Suction pressure	Concentration	
Cabin km (kft)	Exhaust km (kft)	ATA (psig)	Subjects	min	mm Hg	Avg O_2 %	Avg Ar %
2.4 (8)	6.1 (20)	2.7 (25)	J/I	1	2.0/3.4	95.0	5.0
				2	3.1/5.9	94.4	4.6
				3	3.6/6.4	91.8	4.3
				4	4.0/8.0	86.9	4.1
				5	5.0/9.6	82.6	3.9
				6	5.1/10.3	80.0	3.8
		2.0 (15)	J/I	1	5.8/5.6	90.5	5.4
				2	18.6/7.7	94.8	4.9
				3	30.7/12.1	94.4	4.4
				4	35.3/13.4	90.6	4.2
				5	32.0/16.6	86.3	4.0
		2.4 (20)[a]	K/J	1	8.1/20.5	93.2	6.8
				2	16.5/43.8	94.2	5.5
		2.4 (20)	L/J	1	4.0/8.5	93.1	5.8
				2	4.6/13.5	94.7	4.8
				3	10.1/23.9	93.9	4.5

[a]O_2 regulator hoses switched.

[b]Subjects employed deliberate alternate breathing cycles.

The breathing resistance data was somewhat more problematic. Figure 4 shows the average mask suction pressure for the exercise period plotted against inlet pressure to the molecular sieve. At inlet pressures of 5.1 ATA and 3.7 ATA (60 and 40 psig, respectively), average suction pressure was in the range from 3 to 5 mm Hg. In nearly all cases the suction pressure increased sharply when the inlet pressure was set below 2.7 ATA (25 psig). At the lower cabin altitude (5,000 ft), suction pressure increased substantially when the inlet pressure fell below 3.7 ATA (40 psig). Ideally, at resting conditions, the maximum resistance to breathing should not result in mask suction pressures in excess of 2 mm Hg (1, 9). Although breathing resistance acceptance is thought to increase with flow (9), the maximum suction pressures observed in the present study (in excess of 15 mm Hg) were only marginally tolerated by the test subjects. In several cases the high breathing resistance contributed to fatigue and early termination of test protocols. These findings indicate a need for development of an improved regulator for molecular sieve oxygen systems.

CONCLUSIONS AND RECOMMENDATIONS

With certain qualifications, dealing primarily with oxygen delivery equipment, the 2-man molecular sieve unit appears ready for preliminary flight test. The unit delivered adequate oxygen concentration for hypoxia protection up to an altitude of 8.5 km (28,000 ft) and, with improved pressure demand regulation will provide adequate and safe oxygen pressure for protection to 13.4 km (44,000 ft). In the 100% delivery mode, however, recognition must be made of the possibility of a noticeable increase in breathing resistance (mild gas starvation) which may obtain at: (a) cabin altitudes below 2.4 km (8,000 ft), and/or (b) bleed air pressures below 2.7 ATA (25 psig). At cabin altitudes above 2.4 km (8,000 ft), the mass flow should not become restrictive except under relatively heavy workloads; i.e., ventilation levels in excess of 25 LPM.

The argon concentration in the molecular sieve product gas measured from 1.8% to 5.2%. At these concentrations, it is considered unlikely that argon will present any significant risk of decompression sickness (4). No symptoms of decompression sickness were reported or observed in any of the manned test runs. However, it should also be mentioned that no decompression problems were expected due, in part, to the relatively short period of time at altitudes over 7.6 km (25,000 ft). Animal studies are currently ongoing at the USAF School of Aerospace Medicine using a Doppler technique to determine the number of intravascular bubbles formed with 100% oxygen, and with breathing gas mixtures containing either argon or nitrogen as diluents.

We recommend that the flight test program incorporate an improved pressure demand oxygen regulator designed for use with the molecular sieve system. The modified CRU-68 regulators employed in this study were only marginally adequate in terms of breathing resistance, and

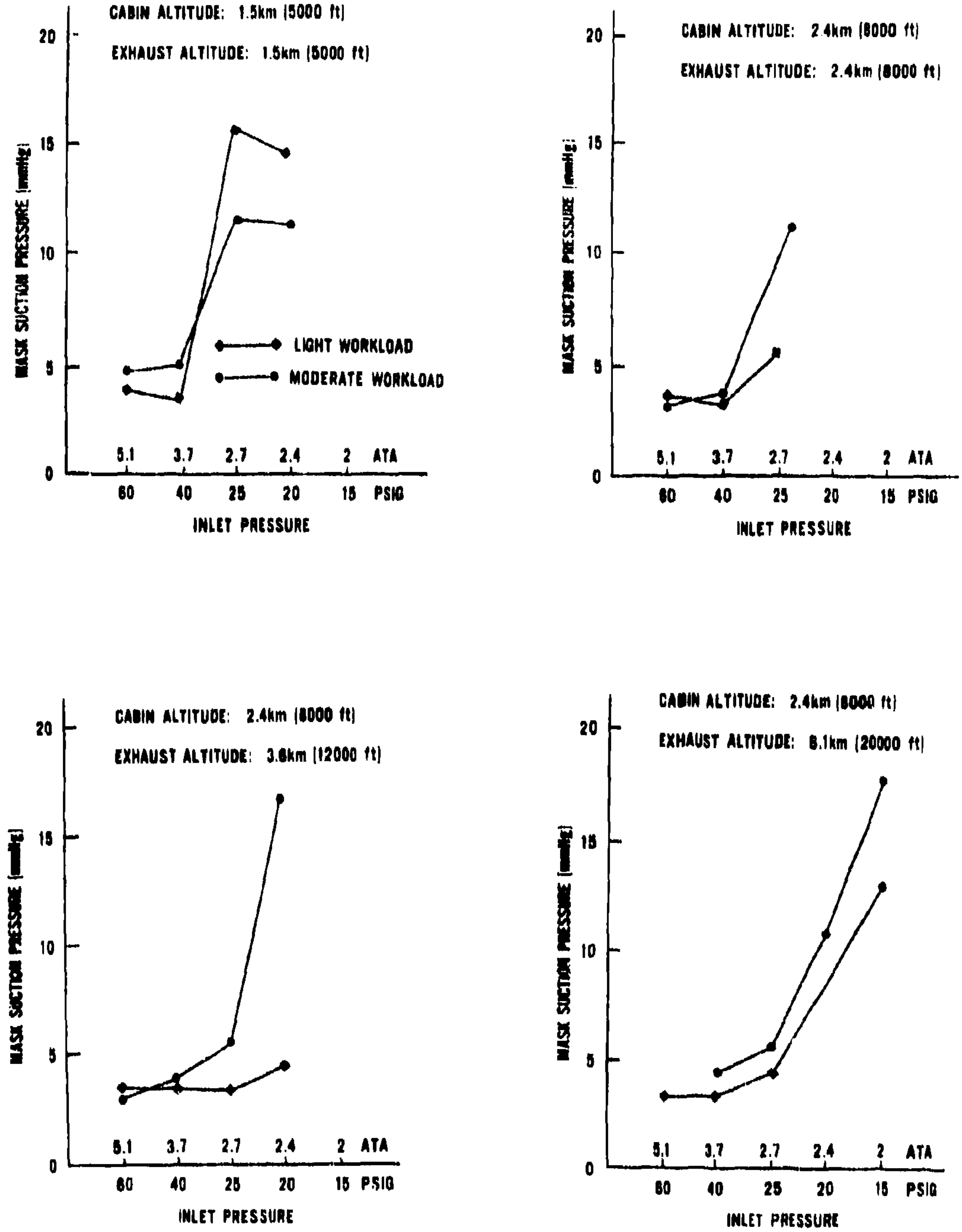

Figure 4. Average mask suction pressure as a function of molecular sieve inlet pressure. Parameter is workload, induced by exercising on a bicycle ergometer.

delivered an excessive positive breathing pressure at altitudes above 9.7 km (32,000 ft). The ideal 100% regulator for molecular sieve application must be capable of supplying the required volume of respiratory gas at low inlet pressures and high flow rates. The pressure breathing schedule for altitudes from 8.5 to 13.7 km (28,000 to 45,000 ft) should only be increased about 10% over that specified in MIL-R-83178, to account for the fact that molecular sieve breathing gas is 95% oxygen.

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