operating characteristics. The pressure data showed that the pump added additional compliance to the system throughout its operation. Cavitation at the pump inlet (confirmed by movies) lowered the resonant frequency of the oxidizer system to the point that it coupled with the structure. The test showed that the resonant frequency of the fuel system also was within the frequency range in question, and, therefore, that both systems contributed to the Pogo phenomenon.

Manned Chamber Testing of the Apollo Prototype Space Suit

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In this note preliminary results on the ventilation efficiency of the Apollo prototype space suit are reported. Two tests were made with human subjects in the entry lock of Republic's 13-ft-diam by 8-ft-long space chamber at a simulated altitude of 35,000 ft. Chamber pressure was controlled automatically by a pressure sensor and pneumatically operated throttling valve system. The suited subject was ventilated with oxygen supplied from an LO_2 source located outside the entry lock (Fig. 1). The oxygen was throttled, metered, and humidified. A manually operated bypass valve controlled the rate of water vapor pickup from a wick in a pressurized water reservoir. Inside the entry lock, the humidity was adjusted by passing the stream through an ice-bath cooler and a centrifugal flow water trap. It then passed through a manifold in which were mounted a mass spectrometer probe, a thermistor, one side of a mercury manometer, and a barometer, and thence to the suit.

The surface of the suit was instrumented with four thermistors, two of which were shielded from radiant heat. The walls of the chamber were heated externally by infrared lamps, and the wall temperature was monitored by a thermistor. The suit exhaust was connected to an exhaust manifold in which were mounted a mass spectrometer probe, a thermistor, and the other leg of the mercury manometer that gave the pressure drop across the suit. The exhaust gases then flowed into the space chamber, from which they were exhausted by the pumping system. A bicycle ergometer was calibrated to measure the mechanical work performed by the subject. The subjects were Republic test pilots whose respiratory quotients were determined in preliminary tests performed at sea-level conditions. Forehead, arm, thigh, trunk, foot, and rectal temperatures, electrocardiogram, and heart rate were monitored.

The ventilation efficiency VE is defined as the ratio of the actual increase in the water vapor content of the ventilation stream to the theoretical increase if the stream were to reach saturation

$$VE = 100\,(\dot{w}_2 - \dot{w}_1)/(\dot{w}_3 - \dot{w}_1)$$

where $\dot{w}_1$ and $\dot{w}_2$ are the water vapor flow rates in and out, respectively, and $\dot{w}_3$ is the theoretical water vapor flow rate out at saturation, all in pounds per minute. For this calculation to be meaningful, the water vapor flow rates used in the foregoing equation had to be chosen at a time when the subject was generating the prescribed metabolic output, and when the water vapor flow rate resulting from this exertion was stabilized. These data were validated by establishing a heat balance, i.e., accounting for all of the heat transfer both into and out of the space suit.

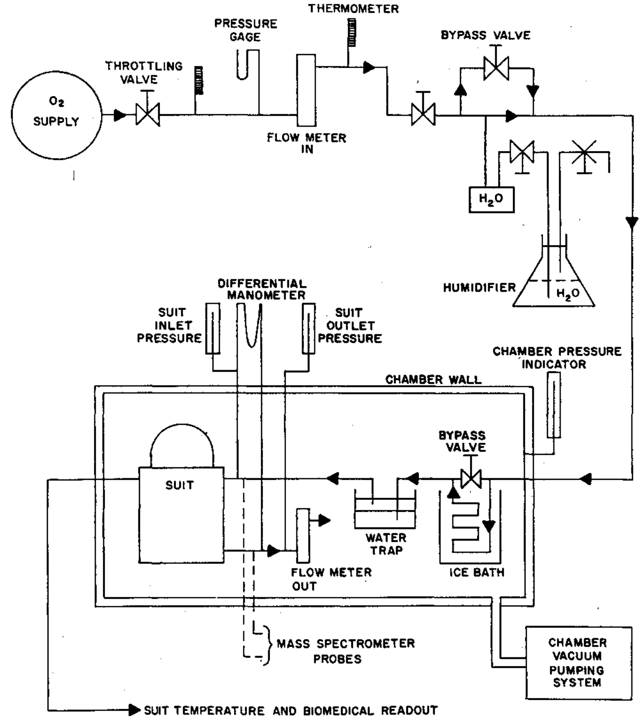

Fig. 1. Liquid oxygen ventilation system.

As illustrated in Fig. 2, the sum of the heat generated metabolically by the subject (Q_{met}) and the change in body heat storage (Q_{stor}) is equated to the total heat removed from the subject by sensible, latent, radiant, and convective heat transfer, and the heat equivalent of mechanical work (Q_s, Q_l, Q_r, Q_c, and Q_m, respectively, all in British thermal units per hour)

$$Q_{met} + Q_{stor} = Q_s + Q_l + Q_r + Q_c + Q_m \qquad (1)$$

The calculation of Q_{met} was based on the rate of expiration of carbon dioxide. The flow of CO_2 was taken as the ratio of the partial pressure of CO_2 to the partial pressures of CO_2 and oxygen times the ventilation flow of oxygen. The CO_2 flow, divided by the respiratory quotient RQ, is equal to the oxygen consumed. The product of the oxygen consumed and its heat equivalent is equal to the metabolic heat output. The formula (adapted from Ref. 1) is

$$Q_{met} = 6230\,\frac{P_{CO_2}\,\dot{V}_{O_2}}{(P_{CO_2} + P_{O_2})RQ}\left[4.69 + \frac{0.36(RQ - 0.71)}{0.29}\right] \qquad (2)$$

where P is partial pressure (torr), and $\dot{V}_{O_2}$ is the oxygen flow (cfm at STP). Body heat storage was calculated from

$$Q_{stor} = 60.1\, Wc_p\, dT_{MB}/dt \qquad (3)$$

where W is the weight of the subject (lb), c_p is the specific heat of the human body (cal/gm°C), T_{MB} is mean body temperature (°R), t is time (min), and T_{MB} was calculated from:[2]

$$T_{MB} = 0.67T_R + 0.33[0.07T_{Fd} + 0.27T_A + 0.19T_{Th} + 0.35T_T + 0.12T_F] \qquad (4)$$

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where the subscript R = rectal, Fd = forehead, A = arm, Th = thigh, T = trunk, and F = foot. The sensible and latent heats removed by the ventilation stream were calculated by

$$Q_s = 60\ \dot{V}_{O_2}\rho c_{pO_2}(T_2 - T_1) \qquad Q_l = 60\ h_l(\dot{w}_2 - \dot{w}_1) \quad (5)$$

where subscripts 1 and 2 again represent in and out, respectively, ρ is density of O_2 (lb/ft³), and h_l is the latent heat of vaporization of water (~1040 Btu/lb at the body temperature involved).

The water flow rates $\dot{w}_1$ and $\dot{w}_2$ were determined from partial pressures by the mass spectrometer and the total flow rate. The ideal gas equation was used with an appropriate conversion factor: $\dot{w} = 0.0325\ P_{H_2O}\ V_{O_2}/T$, where $\dot{w}$ = water vapor flow rate (lb/min), P = partial pressure of water vapor (torr), $\dot{V}_{O_2}$ = oxygen flow rate (ft³/min), and T = temperature (°R).

Radiant heat exchange between the suit and the walls was calculated from

$$Q_r = F_g F_e A \sigma (T_w{}^4 - T_s{}^4) \quad (6)$$

where F_g = geometry factor, F_e = emissivity factor, A = area (ft³), σ = Stefan-Boltzmann constant, T_w = wall temperature (°R), and T_s = suit surface temperature (°R). Convective heat flow from the suit to the ambient environment was determined by

$$Q_c = 4AkP_r{}^{1/2}(0.952 + P_r)^{-1/4}G_r{}^{1/4}(T_2 - T_s)/3X \quad (7)$$

where A = area (ft²), k = thermal conductivity of oxygen (Btu/hr-ft²-F/ft), P_r = Prandtl number of oxygen, G_r = Grashof number of oxygen, T_2 = temperature of oxygen (°R), and X = characteristic dimension of suit (assumed to be unity).

It was also necessary to convert the mechanical work performed on the ergometer into its heat equivalent. This was calculated by multiplying the pedal speed (ω, rpm) by the tangential force exerted (K_p, kg) and correcting for the units to give the heat equivalent rate (Btu/hr)

$$Q_m = 3.34\ K_p\omega \quad (8)$$

A time-of-flight mass spectrometer continuously sampled and analyzed the gas from the exhaust manifold. Figure 3 shows a typical strip-chart record for CO_2. The lower trace is the partial pressure of CO_2 generated by the subject. It has a regular, cyclic pattern except for an interval A during which the subject was speaking. The upper trace is the integration of the lower trace; each vertical excursion represents a constant time-pressure product (torr-sec) of CO_2 partial pressure output. The sum of the vertical excursions during a representative number of respiratory cycles was divided by the time interval for these cycles to determine the average partial pressure of CO_2 during the interval. The water vapor levels measured were relatively steady. As the subject approached a state of equilibrium at a given Q_{met}, P_{H_2O} increased to a plateau and remained constant, except for occasional momentary fluctuations.

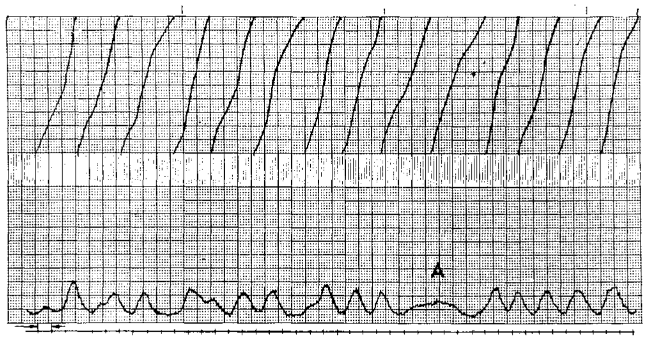

Fig. 3. Carbon dioxide partial pressure curve.

Prior to the test, the subject was assisted by two technicians, his inside observer and the chamber operator. After instrumentation and dressing were completed and base-line data were recorded, the subject and his inside observer entered the chamber and were placed on 100% oxygen for 2 to 2½ hr before actual flight. During this period all of the instrumentation connections were completed, and operation of each component was verified. Ascent to experimental altitude was then accomplished at a rate of approximately 1500 fpm. At experimental altitude, the chamber was placed on automatic altitude control and carefully monitored. The excursions on automatic control were less than ±50 ft from the experimental altitude. Descent to ground level after the run was accomplished manually at ~2000 fpm. When ground level was reached, final data were taken. All of the preflight measurements were then repeated.

The results of the first test are plotted as four points on a curve of oxygen flow vs total heat removed by the stream (Fig. 4). Curve A represents the theoretical maximum amount of heat (both sensible and latent) that could be carried by the stream at various flow rates if the stream were to enter at 43°F carrying water equivalent to saturation at 32°F and were to leave saturated at T_2 (varied from 88° to 91°F). Curve B represents the theoretical heat-carrying capacity of the stream taken at inlet conditions of 43°F saturated and outlet conditions of 93°F saturated with an inlet pressure of 3.73 psia. The temperature of 93°F was

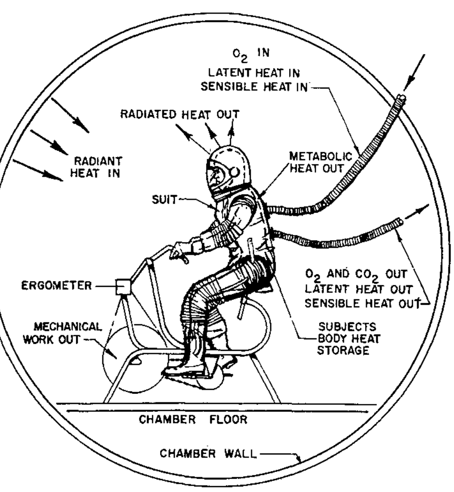

Fig. 2. Heat exchanges of space suit ventilation tests.

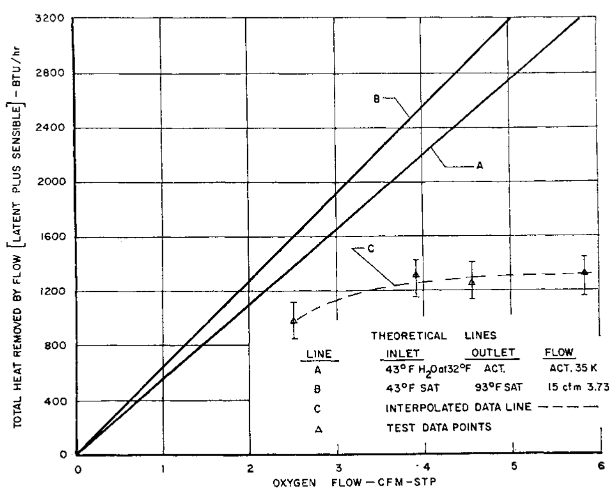

Fig. 4. Oxygen flow vs heat removed, test 1.

Table 1 Thermal balances from second test

Heat load	Ergometer setting, K_p 1.5	1.0
Heat generated (Btu/hr):		
Metabolic output (Q_{met})	1655	1080
Body heat loss (Q_{stor})	0	167
	1655	1247
Heat removed (Btu/hr):		
Sensible (Q_s)	149	121
Latent (Q_l)	1292	956
Loss to ambient ($Q_r + Q_c$)	−50	−50
Mechanical work (Q_{mech})	250	167
	1641	1194

chosen as a realistic theoretical outlet temperature based on experimental data. Curve *C* represents the test data; the vertical line through each data point represents the estimated error range. Comparison of Curve *C* to Curve *A* at 4 cfm indicates a ventilation efficiency of 58%. The thermal balances in Table 1 were established during the second test.

The ventilation flow rate remained constant at 4.1 cfm at STP. The heat loads removed by the stream ($Q_s + Q_l$) at 1.5 K_p work load and 1.0 K_p work load were 1441 and 1077 Btu/hr, respectively. The mean body temperature was 1.2°F higher at stabilization during the 1.5 K_p work load than during stabilization at 1.0 K_p work load. Excessive sweat, during the 1.5 K_p work-load period, "pooled" in the lower sections of the space suit and was relatively unavailable to the ventilation flow. The mean body temperature was steady during the stabilization period at 1.5 K_p work load and continued to decrease during the 1.0 K_p work load. From these limited results, it appears that the subject would have maintained an acceptable mean body temperature (within the physiological limitations of dehydration and fatigue) indefinitely when working at a 1.0 K_p load with a 4-cfm-at-STP ventilation flow rate, and that this flow rate probably is adequate for a 1.5 K_p work load. However, it must be noted that the Q_l's measured correspond to the evaporation of approximately 0.9 to 1.3 lb/hr of body water, so that dehydration will result with prolonged work in the space suit. Hence, means for replacing lost water and electrolytes must be provided in the final design and included in the space suit's operational requirements.

Conclusion

Suited subjects at 35,000-ft simulated altitude, instrumented for electrocardiograms and rectal and skin temperatures, performed work satisfactorily on a bicycle ergometer at a constant metabolic rate (1500 Btu/hr) while the ventilation rate was successively increased from 2.5 to 5.8 cfm STP and at different metabolic rates (1080 and 1655 Btu/hr) while the ventilation rate was held constant at 4.1 cfm at STP. At a work load of 1.5 K_p on the ergometer, the total heat leaving the subject was calculated to be 1641 Btu/hr (sensible, 149; latent, 1292; mechanical, 250; convective and radiant, −50) compared to a metabolic generation rate (as indicated by CO_2 production) of 1655 Btu/hr. Results of the first test (Fig. 4) suggest that the heat removed by the ventilation stream would not be significantly increased by a flow rate greater than 4 cfm at STP, at which the ventilation efficiency was 58% for Q_{met} = 1500 Btu/hr. These limited data suggest that the suit ventilation is adequate for continuous work at the levels investigated, but that body dehydration would result from prolonged work in the suit.

References

[1] Bard, P., *Medical Physiology* (C. V. Mosby and Co., St. Louis, Mo., 1956), p. 580.

[2] Benjamin, F., personal communication, Office of Space Medicine, NASA Headquarters, Washington, D. C. (July 1964.)

Analytical Model to Determine Aft-End Igniter Design Parameters

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Nomenclature

A	=	area, in.^{2}
a^*	=	sonic velocity of igniter gas, fps
C_w	=	flow coefficient = $(\gamma g/RT)^{0.5}[2/(\gamma + 1)] \times \exp(\gamma + 1)/2(\gamma - 1)$, sec^{-1}
g	=	earth gravitational acceleration, ft/sec^2
M	=	Mach number
$\dot{m}$	=	igniter mass flow rate, slugs/sec
P	=	pressure, psia
$\int PdA$	=	integrated pressure, area force of chamber gas on converging portion of motor exhaust nozzle, lbf
R	=	gas constant, ft/°R
T	=	igniter gas total temperature, °R
V	=	volume, ft^3
v	=	velocity, fps
$\dot{w}$	=	igniter flow rate, lb/sec
Γ	=	$1 + (\gamma - 1)/2\, M^2$
γ	=	ratio of specific heats
ϵ^*	=	ratio of minimum annular flow area between igniter and motor exit cone to the motor throat area

Subscripts

e	=	at motor throat plane for gas leaving motor chamber
i	=	at motor throat plane for igniter gas entering motor chamber
ign	=	igniter
p	=	motor port
t	=	motor throat
to	=	total conditions
0	=	at motor plane entering nozzle converging section for gas leaving motor chamber
1	=	initial or ambient conditions
2	=	pressurized conditions
s	=	static conditions

Introduction

THE conventional igniter for a solid-propellant rocket motor generates hot gas, which impinges on the motor propellant and raises the motor chamber pressure. It is normally positioned in the forward end of the motor. An aft-end igniter is positioned near the motor throat and discharges its gas through the motor throat into the motor chamber. Design values for mass flow rate and operating pressure of the conventional igniter have been determined largely through testing. Such a trial-and-error procedure would be very costly on the 260-in.-diam motor. The analytical model described herein permits the sizing of aft-end igniters to obtain desired motor chamber pressure and igniter-gas penetration prior to propellant ignition. These design criteria are presented as functions of the pertinent motor and igniter parameters, and the equations are presented graphically for an igniter operating at 1000 psia. The analysis does not allow prediction of the over-all ignition transient, which will require more comprehensive treatment.

Analytical Model

The analytical model is based on the following two elementary concepts: 1) the incoming igniter gas expands to the static pressure in the motor throat and requires a portion of the throat flow area; the remaining flow area must be sufficient to allow the same flow out of the motor at the same static pressure at sonic velocity; and 2) the incoming flow must be turned around in order to flow out the motor; since

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