PERSONAL PROPULSION SYSTEM

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FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was performed by the Lockheed-California Company of Burbank, California under Contract No. AF 33(615)-1903. The work was performed in support of Project No. 7184, "Human Performance in Advanced Systems," and Task No. 718405, "Design Criteria for Crew Statioms in Advanced Systems."

Mr. R. H. Moulton, Advanced Systems Design Engineer, was the principal investigator for the Lockheed-California Company. Captain J. N. Schofield of the Crew Stations Branch of the Human Engineering Division was the contract monitor for the Aerospace Medical Research Laboratories. The research sponsored by this contract was started in June 1964 and was completed in December 1964.

This technical report has been reviewed and is approved.

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ABSTRACT

This report describes a laboratory model of a simple manually controlled, tractor type, personnel propulsion unit for use under zero gravity conditions. The device consists of a pair of hand-mounted thrust nozzles with fore and aft thrust vector control. A backpack containing two, high pressure, gas bottles supplies dry nitrogen to the thrusters. A series of tests were conducted to obtain thrust nozzle calibration, valve/nozzle modulation, and verification of the total system to deliver the required thrust. The tests verified that the thrust nozzles were within tolerance. The valve/nozzle combination demonstrated total system performance within specification requirements and with satisfactory modulation characteristics. Further research should include evaluation of the propulsion system in a zero gravity environment.

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SECTION I

INTRODUCTION

An experimental model of a Personal Propulsion System was designed and built for use in evaluating motion dynamics and capabilities when in the Keplerian trajectory flights of the KC-135 aircraft.

The Personal Propulsion System consists of a backpack containing two high pressure military specification cylinders, a connecting manifold, a high pressure dumping regulator, and high pressure and low pressure relief valves and two feed lines each connected to a double acting propulsion valve/nozzle assembly.

Figure I
Personal Propulsion System

The selected system satisfies the following requirements to the greatest degree.

- Simplicity of design and operation
- Demonstration of dynamic control characteristics
- Versatility
- Compatibility with zero G test airplanes and commensurate to adaptability to the extravehicular space task

SECTION II

PROGRAM OBJECTIVES AND AGREEMENTS

In the final configuration the only functional items which had to be specially developed were the hand control valve and the associated fingertip control lever system. A valve which could be modulated and which required low torque to operate was mandatory. Existing design valves were considered but failed to fulfill the requirements. Principal rejections on most valves considered were nonlinear torque for operation and pressure drop. The valve selected was a balanced poppet design which would give the low torque values required for finger tip control as well as low pressure drop and satisfactory modulation characteristics. The following recommendations for change or modification were considered.

1. Strap-loop buckle for hand binding in lieu of Velcro straps
2. Design strengths to be equivalent to those dynamic loads imposed upon the aircraft (KC 135 modified for zero G operation), e.g., 3.5 x basic load x design factor or 3.5 x L_p x 1.5 = 5.25 L_p
3. Add padded head guard and support to protect subject during motion of the head
4. Three sizes of hand grips adjustable to the 5- through 95-percentile man, suited and gloved
5. Determine that hand valve lever lengths can be operated by the short fingered percentile
6. Provide thrust curves for the various ranges
7. Provide nitrogen bottles proof tested to 1.67 times the maximum working pressure of 3000 psig

Recommendation that the bottles be proof tested to 1.67 times the working pressure necessitated reselection of suitable pressure storage vessels. To further improve the requirement of recommendation, the manifold was redesigned and the pressure regulator was nested between the bottles to afford greater protection to the regulator against impacts. In addition, a tubular overturn structure was incorporated. The high- and low-pressure relief valves were relocated on the redesigned manifold to position them within the protected area. The pressure gage was located on the inboard side between the manifold and head rest. Recommendation 6 is covered later in this report under Calibration Test. Recommendations 1, 2, 4 and 5 were incorporated in the design with no particular or specific problems.

SECTION III

ANALYSIS AND DESIGN PARAMETERS

The following analytical procedure was used in performing a detailed analysis on the Personal Propulsion System. The analysis entails basic internal fluid dynamic theory and equations, and is combined with well considered assumptions.

The analysis begins with maximum operating pressure in the nitrogen gas pressurized tanks, proceeds through the tank orifice, through the manifold, regulator, tee, flexible lines (assuming two four inch bends per line) and into the nozzle control valve and nozzle throat.

The computation of the initial mass of nitrogen in the tank is accomplished by establishing an initial tank pressure of 3000 psia, a tank temperature of 530° F, a nozzle chamber pressure of 300 psia a tank gas capacity of 80 cu ft, for a required flow rate equal to 0.3 pounds per second. For isothermal expansion of the nitrogen gas across the tank orifice and through the manifold, a constant pressure and temperature exist.

Expansion across the regulator creates a blowdown pressure drop in the tank, within the order of line pressure and a temperature drop of ten degrees due to adiabatic expansion (Joule Thompson Throttling Effect).

Holding the basic line pressure constant, the pressure losses in the lines, bends, and elbows may be calculated and subtracted from the basic line pressure, yielding the pressure entering the nozzle control valve.

This is followed by a check for critical flow (or unchoked flow) at the throat of the nozzle, using a design pressure drop of 15 psi across the nozzle control valve (the valve manufacturer indicated a 10 psi drop).

Following these computations, the calculation of the throat pressure, throat area and the initial specific impulse are completed.

The regulator employed permits the blowdown pressure to be brought down to within 70 pounds of line pressure. Incorporating this into the analysis, a final tank pressure of 420 psig is obtained and a final tank temperature calculated.

Since the final conditions of the tanks are now known, the mass of usable nitrogen may be computed. With the depletion of the computed usable nitrogen in the tanks, there is an associated temperature drop across the regulator and nozzle control valve, below that of the final blowdown temperature.

Specific impulse is calculated from the computation of the final temperature. The total available impulse is then calculated by averaging the final and initial specific impulse and multiplying this by the total computed usable mass of nitrogen. It is found that the value of the total impulse obtained falls well above the required delivered minimum total impulse of 400 pounds per second.

While design calculations and performance measurements are based on a final tank pressure of 420 psig, the regulator employed will permit operation down to complete tank drainage. The regulator will permit continued bleed down, following the upstream pressure drop to, or less than, the preset pressure of the regulator.

Detailed design calculations and tank sizing calculations are shown in Appendix II.

SECTION IV

CALIBRATION TEST

This test section covers the work performed to substantiate the system performance.

OBJECTIVES

The objectives of this test were:

- Verify nozzle thrust levels
- Determine modulation characteristics of valve/nozzle combination
- Verify capability of the total system to deliver the required thrust.

Approach

The cylinder/manifold assembly was hydrostatically tested with water to a proof pressure of 4500 psi.*

The assembly was then modified to include a low-side pressure gauge and shutoff valve in one of the two propulsion valve circuits. The propulsion valve was mounted on a platform scale with the nozzle pointing vertically upward so that the thrust reaction would apply a direct download on the scale platform. A faceplate was clamped in position behind the valve shaft operating lever so that the lever could be clamped firmly in a specified and identifiable position to satisfy test requirements. The propulsion valve was connected to the pressure manifold by means of the same hose which will be used in the operational configuration.

Test Procedures

For convenience and economic reasons it was decided to fill the pressure cylinders to a pressure of 1500 psi and refill at 500 psi.

Valve operating lever positions to be checked were: full-open, 3/4-open, half-open and 1/4-open. These settings were to be repeated for each of the three nozzles (5, 10 and 15 lb. nominal thrust level). All runs were to be made at a regulator setting of 375 psi. Wide open thrust with the 10 lb. nozzle was to be rechecked with both nozzles operating wide open.

Bottle pressure was brought up to 500 psi and the regulator was set at 375 psi which finally settled out at 370 psi. The bottle pressure was then raised to 1500 psi and was accompanied by a drop in regulator pressure to 342 psi (no-flow). The pressure drop was considered to be a normal characteristic of this regulator. Downstream regulated pressure decays at the rate of 2.4 psi per 100 psi increase in upstream pressure.

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* The cylinder/manifold assembly was later proof-tested successfully at 5000 psi

The net result of this regulator characteristic was inability to stabilize the scale indication. Decay of bottle pressure during thrust nozzle operation was accompanied by a rising pressure out of the regulator which, in turn, produced a steady rise in thrust readings. Thrust readings, therefore, were taken as soon as the scale needle stopped oscillating. Regulator pressure was read simultaneously. Figure 3 depicts regulator pressure against upstream pressure. The particular regulator had somewhat more drift than the manufacturer's specification. Results of these tests are recorded in the table in figure 2. Figure 2 plots thrust against valve control lever position for each of the three nozzles. It was discovered on the first test run that there was little or no difference in thrust level between full open and 3/4-open operating positions. Therefore it was decided to omit the 3/4-open position and substitute a 1/8-open position. Upon completion of the single nozzle tests, a final test was made with both the left and right nozzle full open, using the 10-lb nozzles to verify capability of the regulator and manifold to handle the flow.

Discussions

Figure 2 indicates that there is virtually no modulation capability in the valve/nozzle combination and that modulation must be of the pulse-width type rather than the throttling type.

Nozzle performance in the case of the 5-lb and 10-lb nozzles is within tolerance. The 15-lb nozzle is slightly under the specification in terms of maximum thrust. Inspection of the curve on figure 1 indicates that a small increase in pressure may raise the thrust to the lower limit of tolerance. A slight increase in nozzle diameter will accomplish the same thing. Pressure downstream of the regulator was 348 psi for the thrust level recorded. Had this test been continued until bottle pressure was 500 psi and regulator outlet pressure was 370 psi, thrust level of the 15-lb nozzle would have been within tolerance. Figure 3 depicts regulator pressure drift versus upstream pressure. Point scatter on this curve indicates a certain amount of erratic performance. (This scatter may not be entirely caused by the regulator. The pressure gauge was a good quality industrial gauge, but it was not a laboratory type).

The final two-nozzle flow test was accomplished in two steps:

1. Left nozzle thrust was stabilized at full flow.
2. Right nozzle was then opened wide and effect on left nozzle thrust was noted.

Results confirmed the capability of the system to support full flow from two nozzles with no degradation in performance. Because of regulator downstream pressure drift, thrust could not be stabilized. The characteristic of left nozzle thrust appears in figure 4. The characteristic to the left of the center dividing line is that of left nozzle flow only. The characteristic to the right of the center dividing line is that of two nozzles flowing. The change in rate of thrust rise is caused by the change in rate of bottle pressure decay.

TEST CONDITION	HI-PRESS GAGE INITIAL	HI-PRESS GAGE FINAL	LO-PRESS GAGE NO-FLOW	LO-PRESS GAGE FLOWING	THRUST (LB)
5 LB NOZZLE					
FULL-OPEN	1060	1000	352	348	5.37
1/2-OPEN	1000	820	357	355	5.34
1/4-OPEN	820	660	362	361	4.94
1/8-OPEN	660	---	366	363	1.52
10 LB NOZZLE					
FULL-OPEN	1500	1040	348	340	10.17
1/2-OPEN	840	470	362	360	9.96
1/4-OPEN	1400	1220	345	340	6.42
1/8-OPEN	1220	---	350	345	1.22
15 LB NOZZLE					
FULL-OPEN	1490	660	342	342	14.50
1/2-OPEN	1040	700	355	350	13.53
1/4-OPEN	1350	1040	347	345	7.47
1/8-OPEN	1490	1390	345	342	1.02

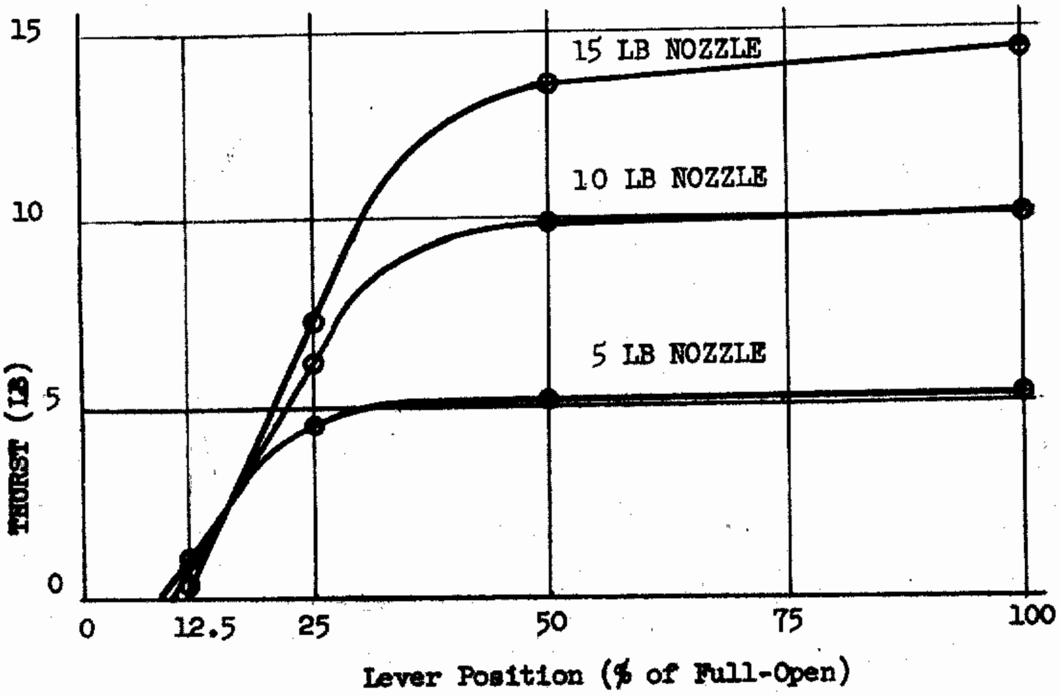


Figure 2

Nozzle calibration

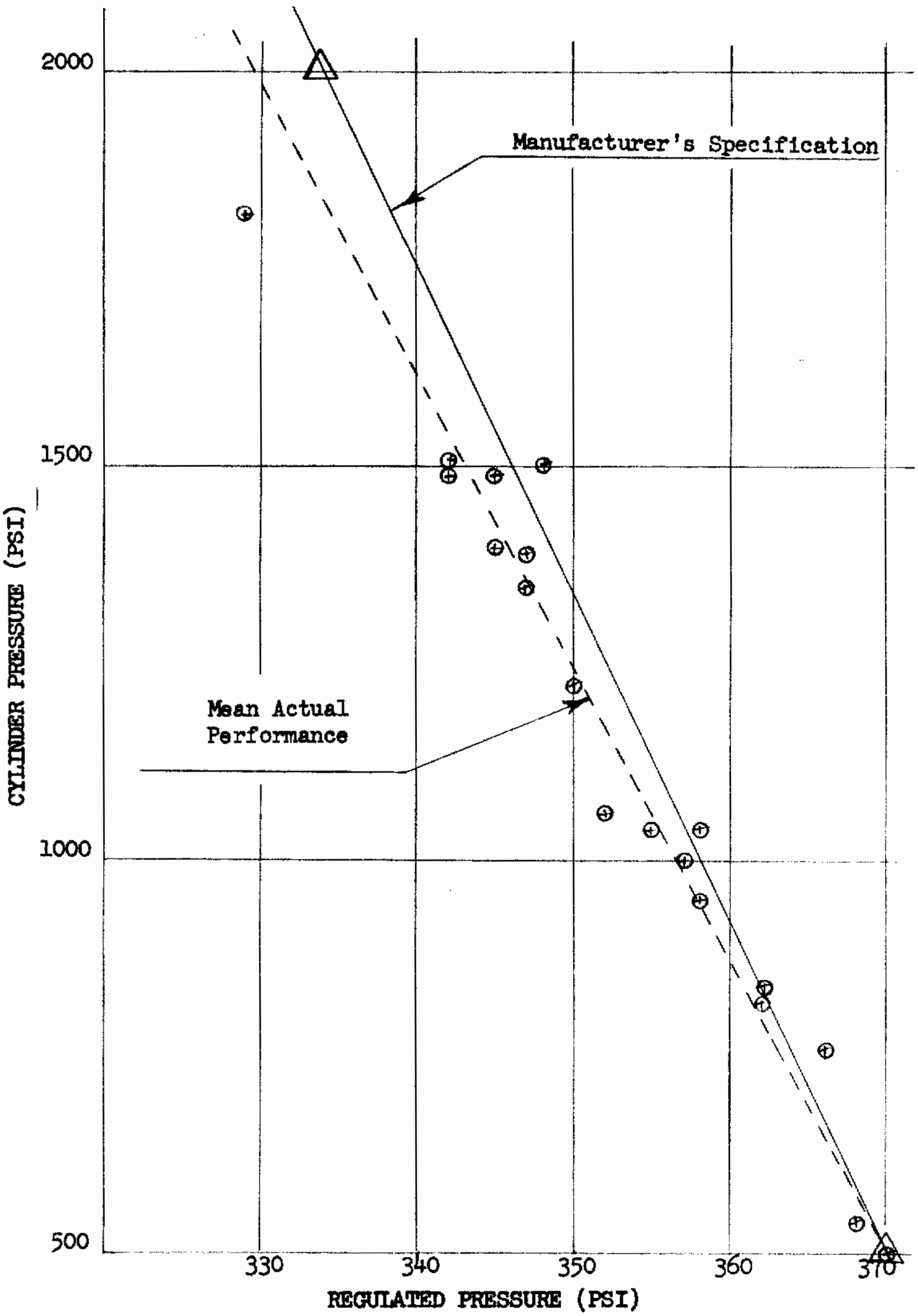


Figure 3

Regulator performance

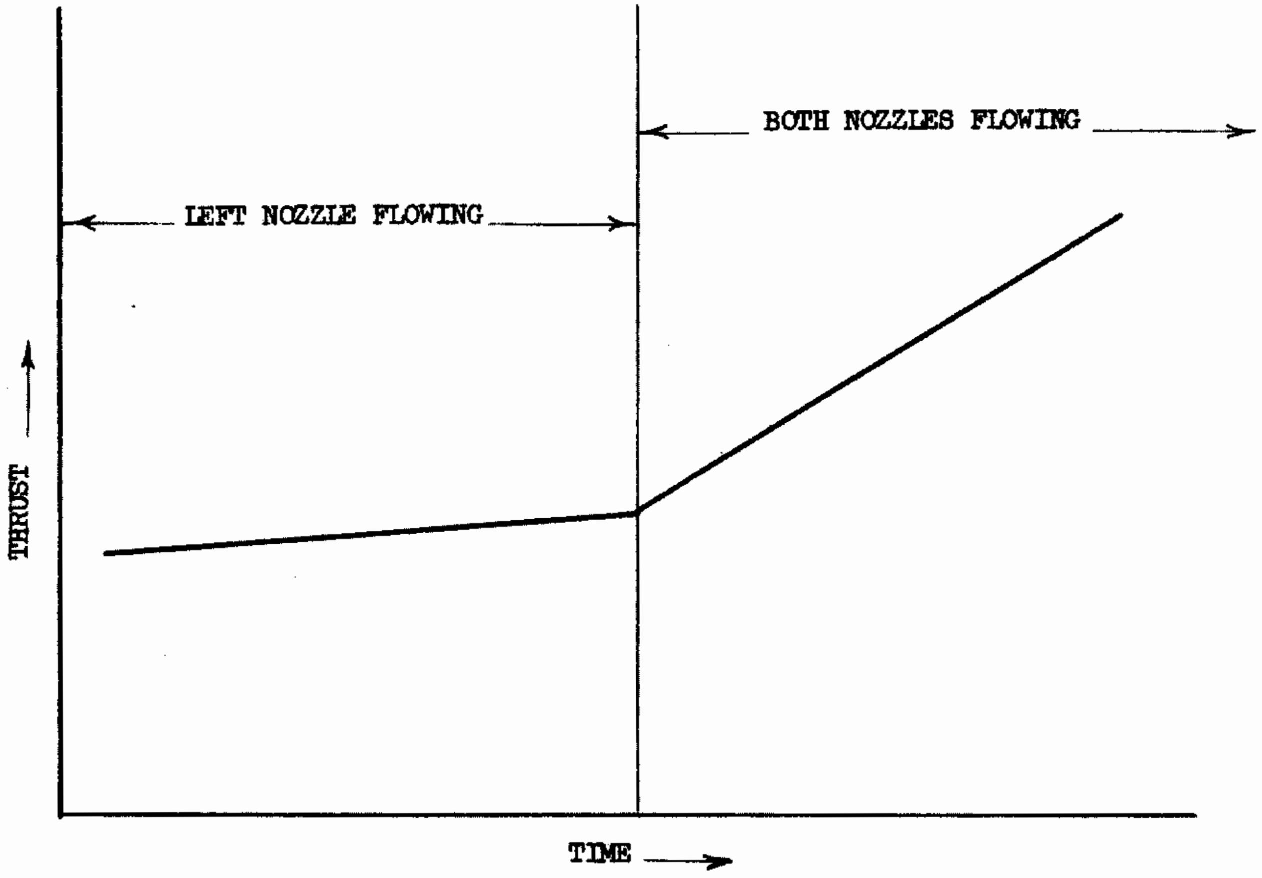


Figure 4

Effect of flow rate on thrust

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The foregoing data are sufficient to support the following conclusions:

- Pressure bottle/manifold combination successfully withstood proof pressure with no permanent deformation.
- Thrust nozzles are within tolerance.
- Total system thrust and flow capabilities are within specification.

It is recommended and desirable that this personal propulsion system be evaluated in a program utilizing the KC-135 for producing the zero g environment.

Further refinement in the present design should be considered.

APPENDIX I

OPERATION AND MAINTENANCE OF THE MODEL CL 650 PERSONAL PROPULSION SYSTEM

INTRODUCTION

Basic features of the Personal Propulsion System as used in the contractor's 'in-house' simulator operation were incorporated into this configuration. Simplicity of design and maximum use of off the shelf hardware were two of the basic design requirements. Thrust modulation requirements were determined on the basis of past experience in simulator operation. Safety of the system is of paramount importance and features of the design include high and low pressure relief protection, structural protection against mechanical damage to the system from accidental impact and generous load factors on the pressure storage and routing system.

In the Personal Propulsion System the final configuration incorporates co-axial thrust units attached to the back of each hand. This location has proven to be the most advantageous because of providing maximum maneuverability with a minimum number of thrust units and maximum safety, because of the ability to control maneuvering successfully in emergency with only one unit operating. As shown in figure 1, the support assembly provides protection of critical components in all directions should the subject fail to reach his normal seat station at the end of the zero g maneuver. Heavy loads from the pack due to onset of positive g forces will be transmitted into the aircraft structure through the propulsion system support structure over a distributed or multiple area. The weight of the system components carried on the back of the subject is ninety-one pounds and is distributed through the fiberglass pack over the upper area of the subject's body. Therefore, even in the most adverse position at pull out maneuver, such as prone beneath the full weight including the g load of the back pack unit, injury to the subject is improbable.

DESCRIPTION

The Personal Propulsion System is a back worn propulsion supply unit carrying nitrogen at 3000 psi. The two pressure vessels, each of which has a volume of 80 cu ft stpd are manifolded together with a stainless steel unit. The manifold includes ports for direct mounting of a high flow, dome type pressure regulator, system storage pressure gage, strut type filler valve, high pressure relief valve set at 370 psi is mounted on the outflow side of the pressure regulator. All units on the manifold are mounted to provide protection against impact and are located so as to be protected to the greatest degree possible by the tubular guard frame. Two light-weight medium pressure hoses are routed from the tee to the coaxial hand valves. These are positioned on the hands by a metal band which surrounds the back of the hand and palm and are secured by a slide loop type buckle at the wrist. The operating levers on the valves are operated with the index and finger controlling forward thrust and the second finger reverse thrust respectively. The list of parts is as follows:

CL 650-1-1	Personal Propulsion System Assembly
CL 650-1-2	Propulsion Control Assembly
CL 650-1-3	Lever Assembly Propulsion Control Forward Thrust
CL 650-1-4	Lever Assembly Propulsion Control Aft Thrust
CL 650-1-5	Nozzle
CL 650-1-6	Hand Grip Propulsion Control
CL 650-1-7	Manifold Pressure Tank
CL 650-1-8	Housing Assembly Propulsion Control
CL 650-1-9	Tee-Regulator Outlet
CL 650-1-10	Fitting Pressure Tank
CL 650-1-11	Support Back Pack
CL 650-1-12	Buffer - Support Bar Back Pack
CL 650-1-13	Fitting Regulator to Manifold

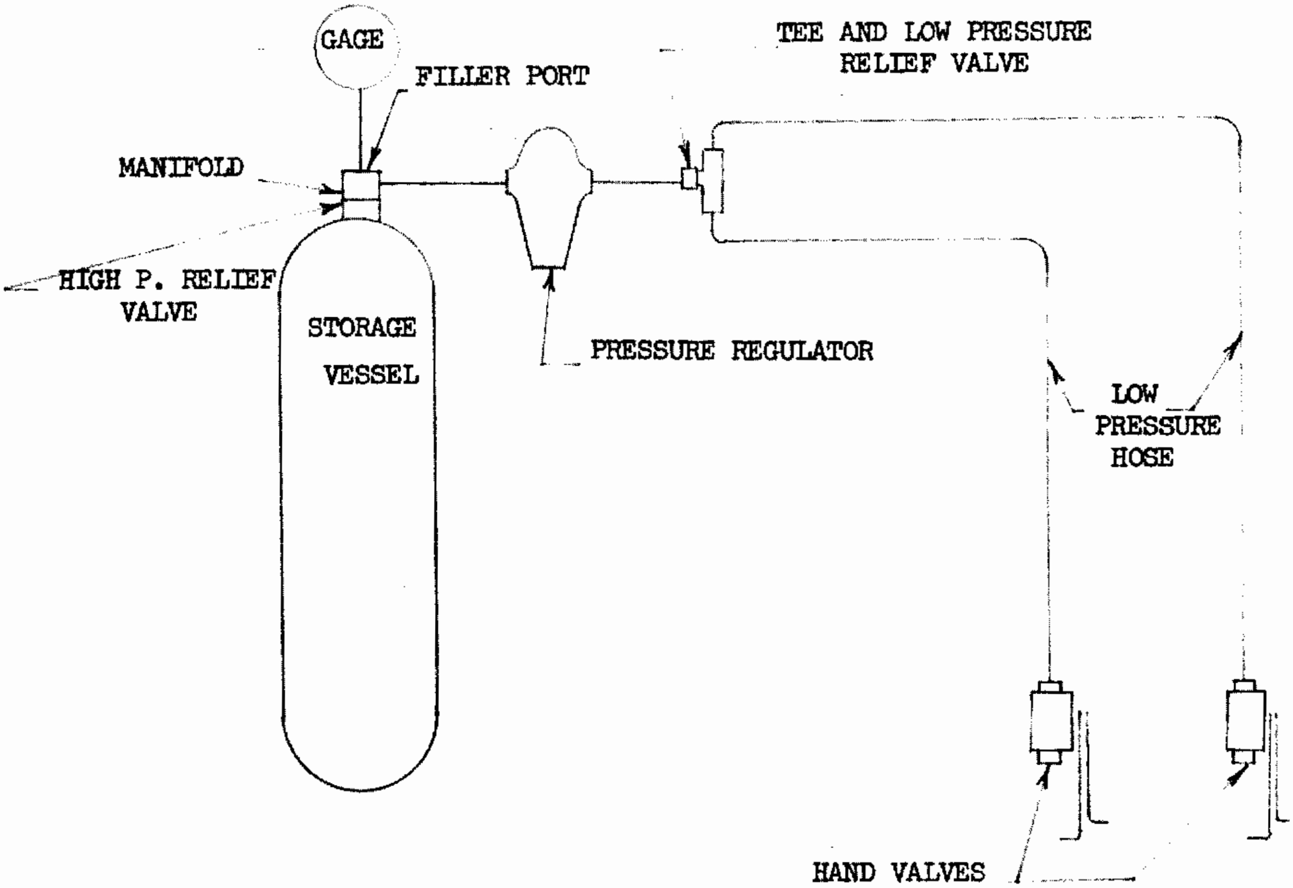


Figure 5
Line diagram of system

OPERATION

The pressure cylinders are filled with clean dry nitrogen through the strut type filler valve mounted on the left hand side of the manifold to a pressure of 3000 psi as read on the unit gage. The two tanks will deliver approximately 9.25 pounds of usable nitrogen, thus providing an estimated total impulse of 425 pound seconds.

The duration of thrust is shown on the curve in figure 6.

Overfilling will result in the high pressure relief valve releasing at 3400 psi. The dome type regulator is adjustable in accordance with the regulator instruction manual furnished with the unit. The regulator is installed so that the two Allen wrenches furnished can be utilized should resetting of the regulated pressure be desired. After filling, the system should be checked for leakage. This procedure can be done audibly or with MIL-L-25567A Leak Detector Solution applied at each joint. When the unit has been completely checked out it is ready for donning. Unless a stationary stowage rack is provided, two men should lift the unit to position on the subject's back. After inserting the arms through the shoulder straps, these should be pulled up to a snug comfortable position. The waist strap is then engaged in the loop type buckle and pulled up tight. The hand nozzle assemblies are now slipped over the four fingers of each hand and the wrist straps secured. Position and ease of operation of the control valves by the subject should then be checked. Three sizes of mounting bands are provided to insure satisfactory fit. Reaction forces on both hands should be experienced by operating each of the two levers on each hand valve. Three sets of nozzles are provided and it should be established that matching pairs are on each valve. The nozzle sizes are designed to provide 5, 10, and 15 pounds of thrust respectively.

The thrust level selection is based on simulator test experience. For the zero gravity tests the most desirable size nozzle combinations should be determined. For example, it may be found that reverse or stopping thrust required may be greater than the forward thrust required. Forward thrust is initiated by depressing the valve lever with the index finger. Experience with the modulation of these valves for both forward and reverse reaction must be gained in practice by the subject in order to develop proficiency and understanding of the propulsion forces available. Figure 7 illustrates the position the subject's body will assume with various nozzle positions relative to the basic center of gravity. After the desired forward progress or velocity is accomplished, operation of the valve lever at the middle finger will provide decelleration, stopping or reverse. If the forward progress of velocity is too great the hands should be stretched forward, palms out, to accept impact loads. This generally should not be required after proficiency with the operation is attained. Gradually various

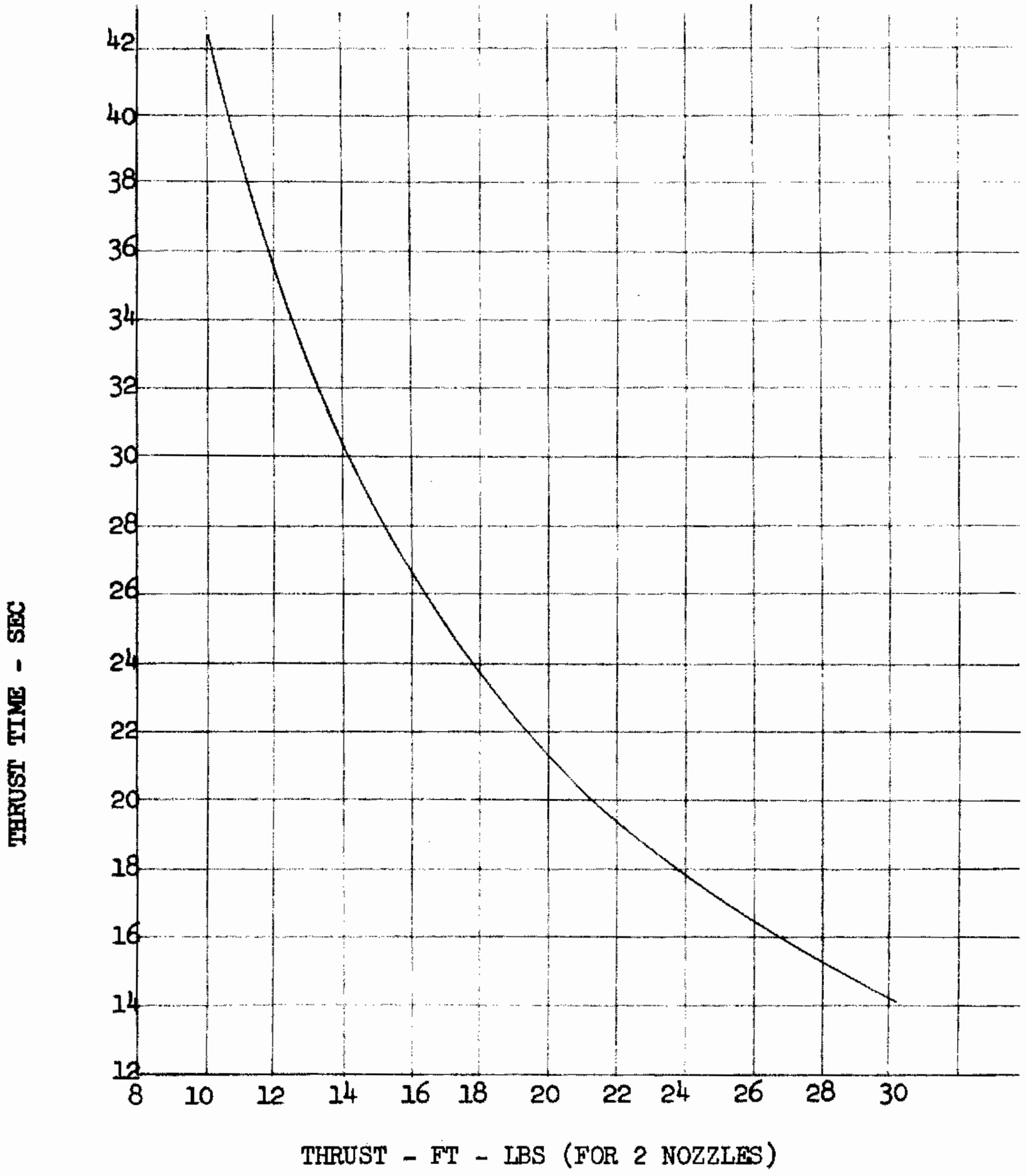


Figure 6

Thrust vs duration

maneuvering abilities will be attainable by pointing the hands in corrective positions for vector change and special maneuvers will be possible by applying forward thrust on one unit and reverse on the other, i.e., to rotate on a point location. After each test operation, supply of pressure should be checked and refilling of the vessels accomplished when the pressure has dropped below 300 psi on the system gage. The system should then be refilled as before with clean dry nitrogen until the storage gage indicates 3000 psi.

The system contains safety provisions in the form of high and low relief valves. As previously mentioned the 3400 psi valve prevents excessive pressure in the upstream side of the regulator. The low pressure valve is set at 370 psi and will release pressure in the event of malfunction of the regulator, protecting the hoses and hand valves. The Personal Propulsion System has been proof tested to 1.67 times the 3000 psi pressure. Catastrophic failures of the system caused by impact are averted by the design of the over-turn structure and protected positioning of protrusions on the manifold unit.

MAINTENANCE

It is of paramount importance to keep all components clean especially in the filler valve area. Only clean dry nitrogen should ever be used in the system and therefore cleaning of the interior components of the pressure regulator and hand valves should not be necessary. However, all parts should be inspected after 50 hours of operation. At the time of complete overhaul the relief valves should also be disassembled and inspected. This work should be done only by qualified, experienced technicians in a clean area. It is advisable to return the components to the manufacturer for this work if the necessary trained personnel are not available. It is recommended that at the time of overhaul the flexible hoses be replaced with new units. When reassembling the components, all 'O' rings and fitting seals should be replaced with new parts. After reassembly the system must be checked for pressure leakage.

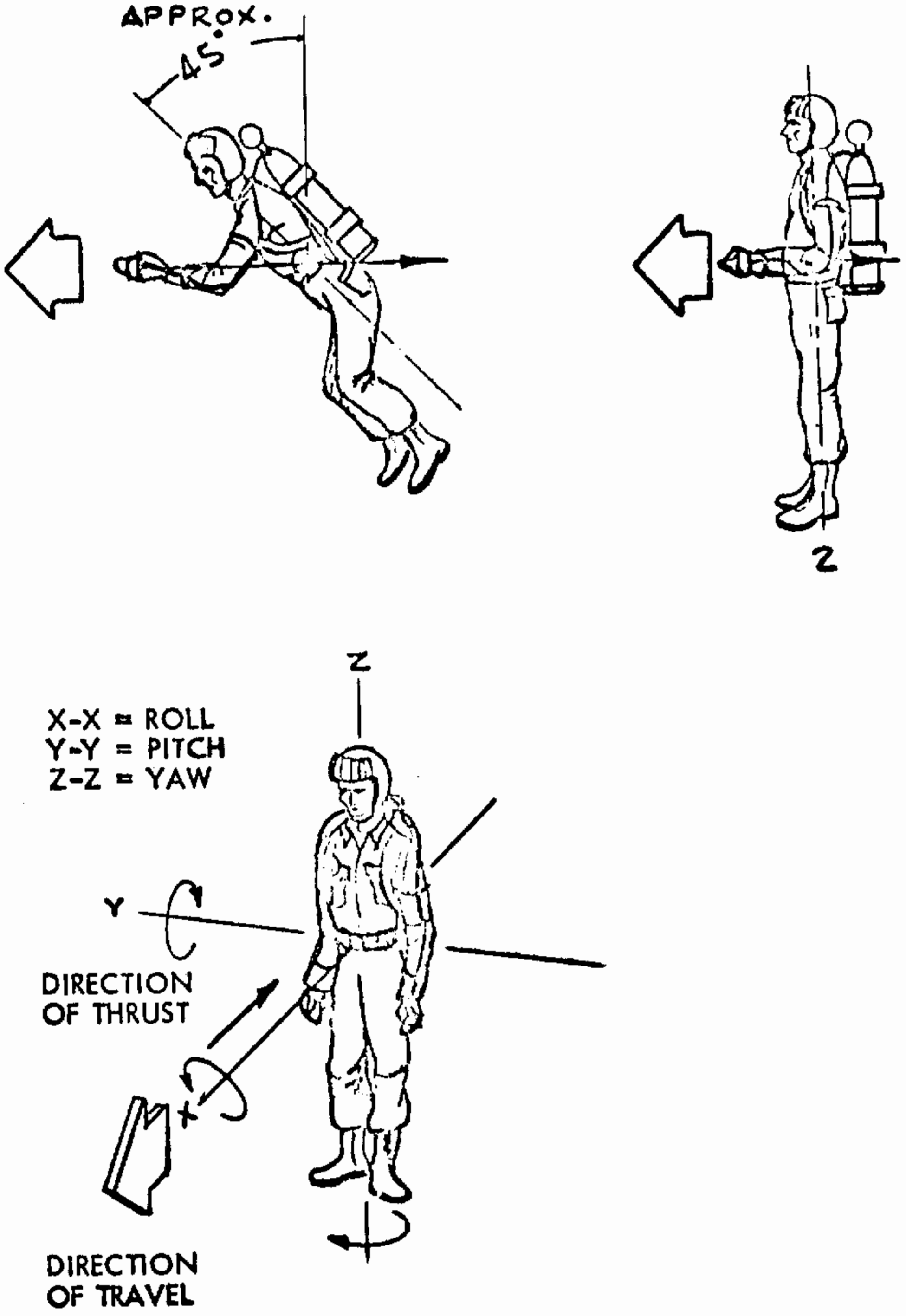


Figure 7 Sheet 1

Zero G Body Positions

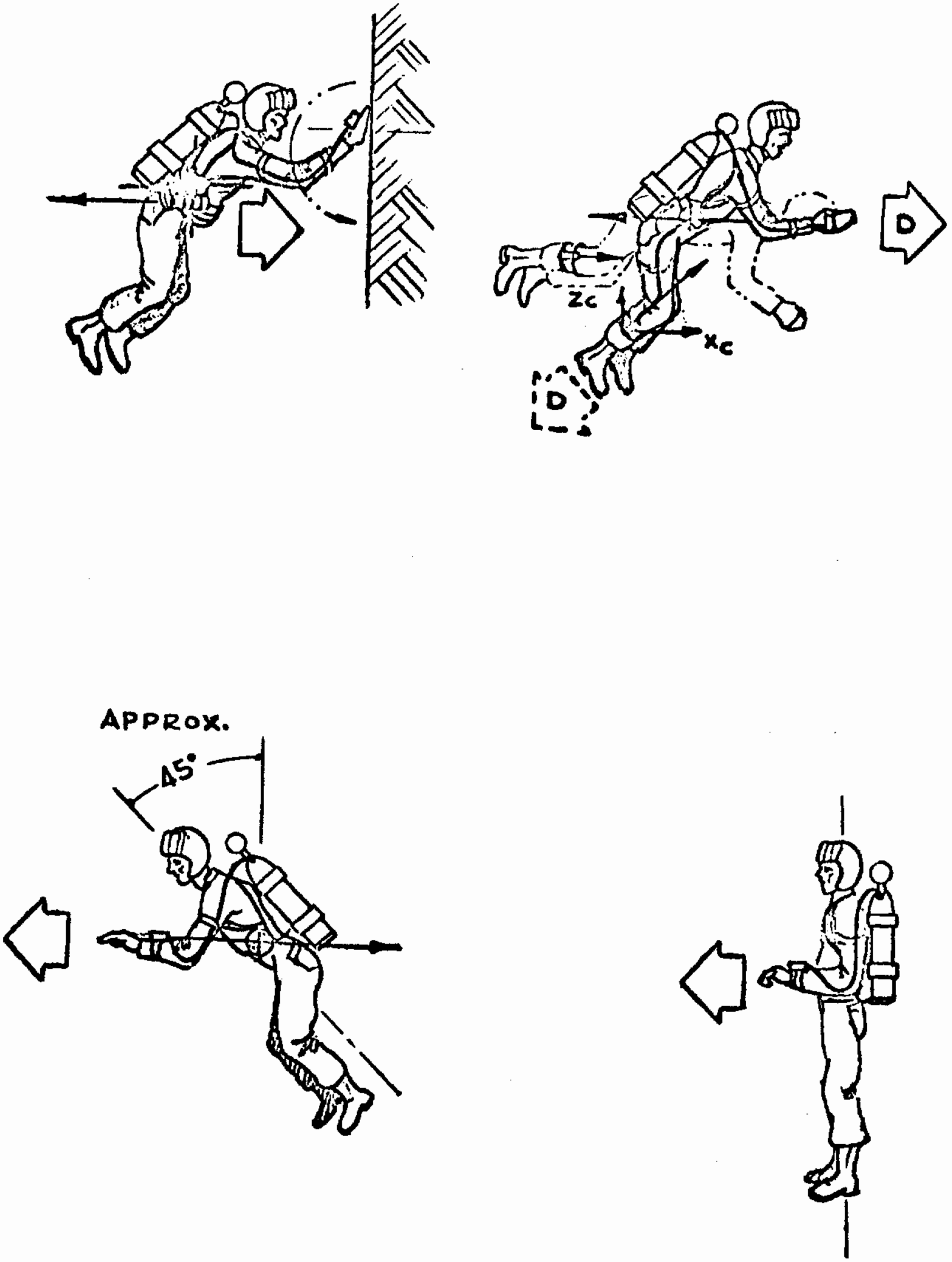


Figure 7 Sheet 2
Zero G Body Positions

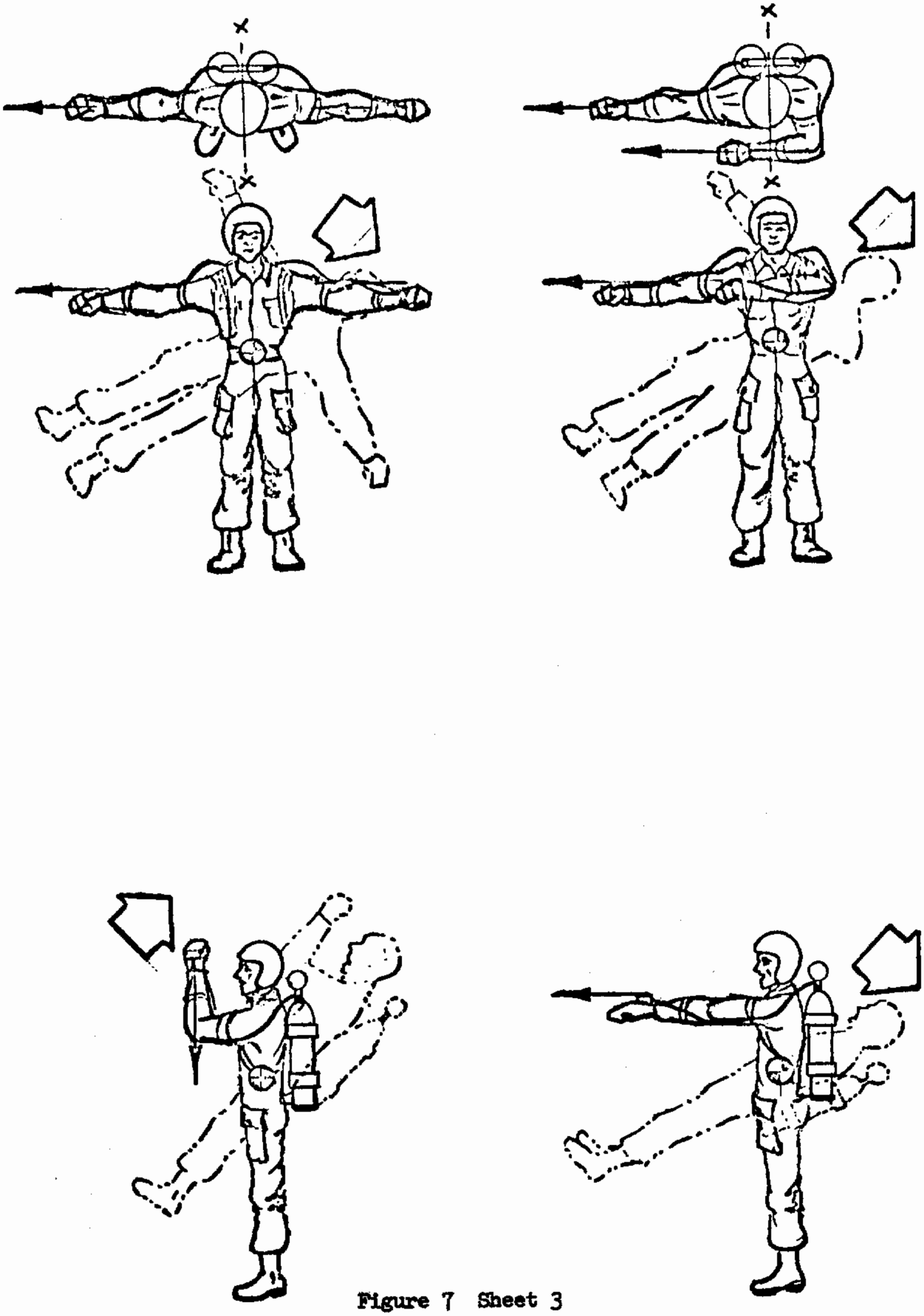
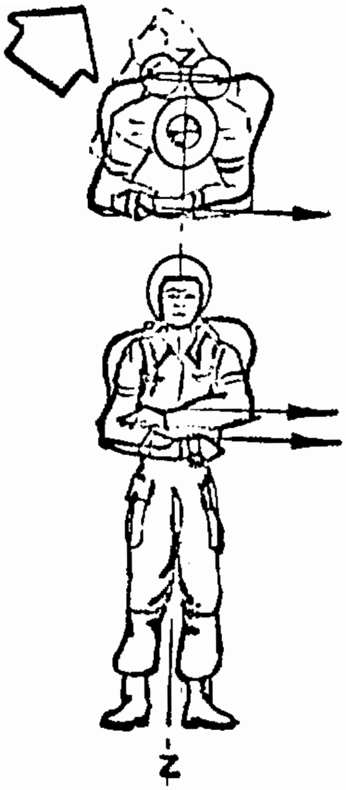
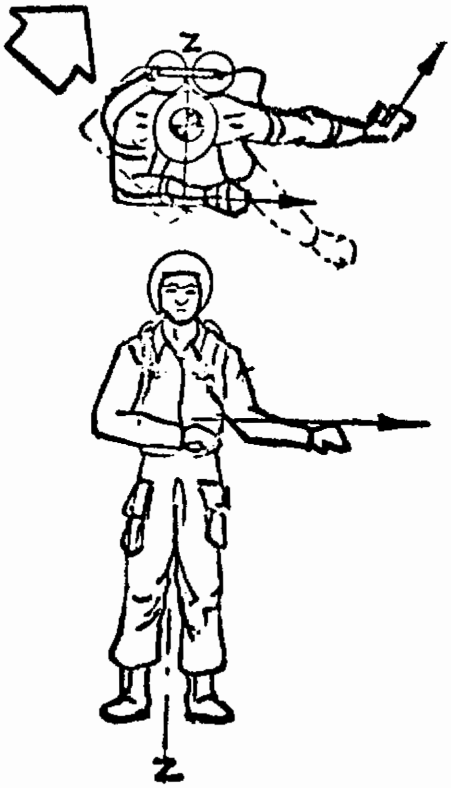


Figure 7 Sheet 3

Zero G Body Positions





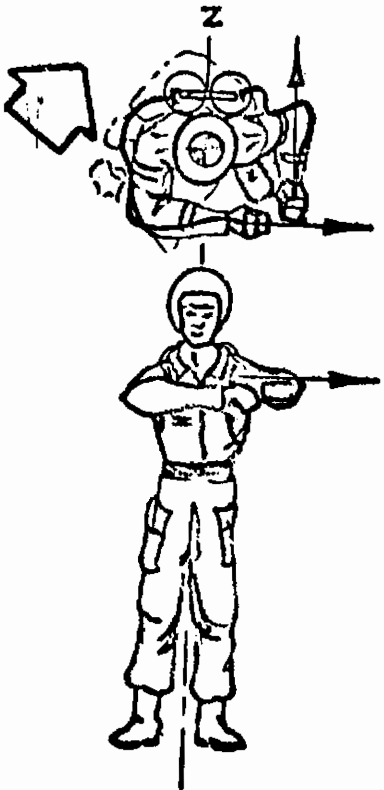


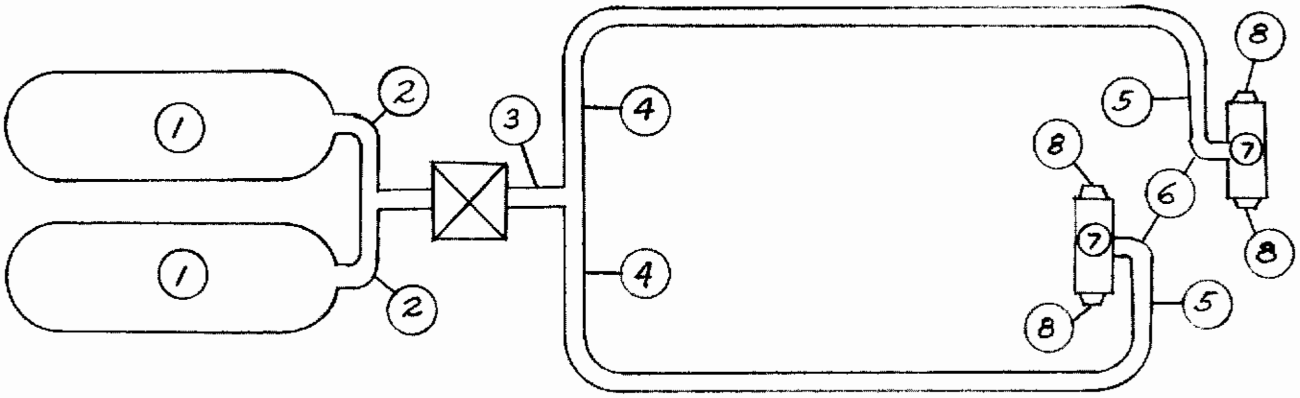
Figure 7 Sheet 4

Zero G Body Positions

APPENDIX II

DESIGN AND SIZING CALCULATIONS

DESIGN CALCULATIONS



Assume at tank (1):

P_1 = 3000 psia

V_1 = 825 cubic in (equiv to 80 cu ft expanded nitrogen)

T_1 = 530°R

G = 1.4 =Cp/Cv (ratio of specific heats of nitrogen)

R = 55.2

$d = P_1/RT_1 = 3000(144)/(55.2)(530) = 430000/29200 = 14.75$ lb/sq ft

Initial mass in tank $M_1 = dV = 14.75\ (825/1728) = 7.05$ lb

At manifold (2)

P_2 = 3000 psia

T_2 = 530°R

Tank throat cross section area: $A_2 = \pi D^2/4 = \pi\ (.75)^2/4 = 0.44$ sq in

Check for choking at tank throat: (let Z = flow rate lb/sec)

Mach no. $M = 2Z\ \sqrt{T}/PA = 2(.3)\ \sqrt{530}/(3000)(.44) = 13.87/1320 = 0.0105$

Critical Mach no (from tables) = .01095 = M*

Since $M < M^*$, loss is negligible

At (3) regulator reduces pressure to:

P_3 = 340 psia (assumed). Assume a 10°R temp drop across regulator (Joule Thompson effect)

$T_3 = 530-10 = 520°R$

$d_4 = (340)(144)/(55.2)(520) = 49000/28700 = 1.708$ lb/sq ft

At line (4):

P_4 = 340 psia

$T_4 = 520°R$

$d_4 = 1.708$ lb/sq ft

Computing velocity at (4):

$V_4 = Z/P_4A_4$ where $A_4 = \pi D^2/4 = \pi(.562)^2/4 = 0.248$

$V_4 = (.3)(144)/(1.708)(.248) = 43.25/.424 = 102.0$ ft/sec

Pressure loss through tee:

Head $h = K_LV^2/2g$ where $K_L = 0.92$ (from tables), g = gravity

$h = (.92)(102)^2/64.4 = 149$ ft (nitrogen)

$\Delta P = hP/144 = (149)(1.708)/144 = 1.765$ psig

$\Delta P = 2$ psig approx

At line (5) $P_5 = P_4 - \Delta P = 340-2 = 338$ psia

$T_5 = 520°R$

Length $L_5 = 37$ in

$d_5 = P_5/RT_5 = (338)(144/(55.2)(520) = 1.695$ lb/sq ft

Dynamic head $q = dV^2/2 = (1/2)(1.695/32.2)(102)^2 = 268$ lb/sq ft = 1.86 psi

Assume two 4 in. radius 90° bends per line.

Bend loss factor = 2   2 x 2 (1.86) = 7.44 psi loss in bends

Line loss:

$\Delta P_L = .0027\ FLSV^2/D$ where L = 37 in, S = 1.695/.075 (from tables), F = .04

$\Delta P_L = .0027(.04)(37/12)(1.695/.075)(102x102/.562) = 140.0$ in. H_2O head

$\Delta P = 140.0\ (0.036) = 5.04$ psig

Total line loss = loss in line + loss in bends = 5.04 + 7.44 = 12.48 psig

At (6) elbow loss:

$P_6 = P_5 - \Delta P$ line loss

$P_6 = 338 - 12.48 = 352.5$ psi

$T_6 = 520°R$

$A = .2475$ sq in $= .2475/144 = .00172$ sq ft

$d_6 = P_6/RT_6 = (325.5)(144)/55.2(520) = 46800/28700 = 1.63$ lb/sq ft

$h = K_L V^2/2g$ where K_L for elbow $= .55$

$V = Z/dA = 0.3/(1.63)(.00172) = .3/.00281 = 106.5$ ft/sec

$h - (.55)(106.5)^2/64.4 = 97.3$ ft (nitrogen)

$\Delta P_E = (97.3)(1.63)/144 = 1.10$ psig

At valve (7): Assume a 15 psi loss across valve

$P_7 = P_6 - \Delta P_6 - 15 = 325.5 - 1.10 - 15 = 309.4$ psia

$T_7 = 520°R$

$A_7 = \pi(.4)^2/4 = .125$ sq in

Checking for choking at valve:

$M = Z\sqrt{T}/dA = .3\sqrt{520}/(309.4)(.125) = 6.85/3.87 = .1770$

$M^* = .196$. Therefore no choke in the valve.

At (9) solving for P_8:

$P_7/P_8 = (d + 1/d)^{**}$ where $** - d/d\text{-}1$

$P_7/P_8 = (1.2)^{3.5} = 1.892$

$P_8 = P_7/1.892 = 309.4/1.892 = 163.3$ psi

Solving for the initial specific impulse:

$$I_{SP_o} = .95\left\{\sqrt{(2R/g)(d/d-1)T_7\left[1-(P_8/P_7)^{**}\right]} + (P_8 - P_1)\,A8/Z\right\}$$

where $** = d\text{-}1/d$

A_8 may be determined by:

$F = A_8 P_7 Cf$ where F = thrust and Cf = coeff of thrust = 1.2404 and $P_7 = 309.4$

$A_8 = F/P_7 Cf$

F	P_7	Cf	A_8	No.
15	309.4	1.2404	.0391	1
10	309.4	1.2404	.0260	2
5	309.4	1.2404	.0130	3

Using no. 1 nozzle:

$$I_{SP_o} = .95\left\{\sqrt{\left[2(55.2)/32.2\right](1.4/.4)\,520\left[1-(163/309.4)^{.285}\right]} + \left[(163-10.9)/.3\right](.039)\right\} = .95\left\{\sqrt{(6235)(.164)} + 19.8\right\} = .95\,(32.1 + 19.8) = .95\,(51.9)$$

$I_{SP_o} = 49.4$ sec

Since the regulator can be blown down to within 70 psi of line pressure,

$P_{line} + 70 = 338 + 70 + 408$ PSI

Assume P_F (final tank blowdown pressure) = 420 psi

Solving for final temp:

$T_F = T_1 \left(P_3/P_4\right)^{**}$ where $** = (d-1)/d = 530 \left(420/3000\right)^{.2355} =$

$530 \left(.1395\right)^{.235} = (530)(.570) = 302°R$

$P_F = P_3/RT_F = (420)(144)/55.2)(302) = 60500/16650 = 3.63$ lb/sq ft

$M_F = d_F F = 3.63\ (825/1728) = 3.63\ (.477) = 1.73$ lb

Musable $= 2\ (M_o - M_F) = 2(7.05-1.73) = 2\ (5.32) = 10.64$ lb. nitrogen

At the end of thrust time, conditions at point (1) are:

$P_1 = 420$ psi $= P_2$

$T_1 = 302°R = T_2$

At (3) assuming a 10°R loss across regulator

$T_3 = T_2 - 10° = 302 - 10 = 292°R$

At (7) we have a 10°R loss across valve

$T_7 = T_3 - 10 = 292 - 10 = 282°R$

Solving for final $I_{SP} = .95 \left\{ \sqrt{(11.99)(282)(.164)} + 19.8 \right\} = .95\ (23.6 + 19.8) =$

$= .95\ (43.4)$

$I_{SP_F} = 41.3$ sec

$I_{SP\ (avg)} = (49.4 + 41.3)/2 = 90.7/2 = 45.35$

Total impulse available

$I_T = MI_{SP\ (avg)}$

$= 10.64\ (45.35)$

$= 482$ lb sec

TANK SIZING CALCULATIONS

For the 725 cu in cylinder

$T_o = 530°R$

$P_o = 3000$ psia

$d_o = P_o(144)/(R)(T_o) = (3000)(144)/(55.2)(530) = 14.78$ lb/cu ft

Blow down to 445 psia

$T_1/T_o = (P_1/P_o)^{**}$ where $** = (d-1)/d = 530\ (445/3000)^{.286} = (530)(.1485)^{.286}$

$T_1 = (530)(.578) = 307°R$

$d_1 = P_1(144)/RT_1 = (445)(144)/(55.2)(307) = 64000/16940$

$d_1 = 3.775$ lb/cu ft

Total usable nitrogen in tank

$Z_T = (d_o - d_1)V = (14.75-3.775)(725)/1728 = (11.005)(.419) = 4.62$ lb/cylinder

Since we have two cylinders, total usable nitrogen in propulsion system

$Z_T = 2 \times 4.62 = 9.25$ lb nitrogen

From design calculation:

Average $I_{SP(Avg)} = 46.1$ sec

Total impulse $I_T = I_{SP(avg)}(Z_T)$

$I_T = (46.1)(9.25)$

$I_T = 426$ pound seconds

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13. ABSTRACT

This report describes a laboratory model of a simple manually controlled, tractor type, personnel propulsion unit for use under zero gravity conditions. The device consists of a pair of hand-mounted thrust nozzles with fore and aft thrust vector control. A backpack containing two, high pressure, gas bottles supplies dry nitrogen to the thrusters. A series of tests were conducted to obtain thrust nozzle calibration, valve/nozzle modulation, and verification of the total system to deliver the required thrust. The tests verified that the thrust nozzles were within tolerance. The valve/nozzle combination demonstrated total system performance within specification requirements and with satisfactory modulation characteristics. Further research should include evaluation of the propulsion system in a zero gravity environment.

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