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AMD-TR-66-4
9 DECEMBER 1966

DEVELOPMENT OF AN INTEGRATED ERGOMETER/LOWER BODY NEGATIVE PRESSURE SYSTEM

PREPARED UNDER CONTRACT NO. AF ^{AF 41(609)-2800} (609)-2800 PROJECT TASK NO. 6700 PB

by
Biotechnology
Lockheed Missile & Space Company
Sunnyvale, California

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F. E. RILEY
C. C. CAIN
A. L. WEITZMANN

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AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
BROOKS AIR FORCE BASE, TEXAS

FOREWORD

This project was initiated by the Headquarters of the Aerospace Medical Division at Brooks Air Force Base, Texas. The development of the integrated Ergometer/LBNP was conducted by the Biotechnology organization of the Lockheed Missiles & Space Company, Sunnyvale, California under Contract 41-(609)-2800. Mr. F. E. Riley, Bioengineering, was the Project Leader. Air Force technical direction and management was provided by Lt. Col. J. W. Ord/AMRO, and Maj. K. H. Cooper, Director, Aerospace Medical Lab (Clin), Wilford Hall USAF Hospital. The work was performed in support of Project Task Number 6700 PB, "Development of Space Flight Devices to Diminish or Prevent the Deconditioning Effects of Weightlessness and Other Environmental Factors." The project was initiated in August 1965 and was completed in June 1966.

This technical report has been reviewed and is approved.

J. W. ORD

ABSTRACT

The object of the program was to provide prototype equipment for use by the USAF in laboratory studies of physiological deconditioning similar to that which results from space flight. Three successive versions of an integrated Ergometer/Lower Body Negative Pressure (LBNP) System were delivered to AMD. The ergometer consists of a self-powered bicycle type unit with a solid-state electronic control system to maintain constant generator output regardless of pedal rotation speed. Recording capabilities are provided for a tachometer, and a wattmeter. Provisions are made to attach power consuming or power storage devices to the ergometer. Work loads up to one horsepower can be accommodated. The ergometer was calibrated using a dynamometer with speed reducer. The LBNP chamber is fully collapsible and employs circumferential rings to support the side loads. For ground applications longitudinal support members are used to carry the axial loads. The waist seal is a single molded unit and is removable from the chamber. The chamber has provisions for 19 leads of bioinstrumentation. A fail-safe overpressure control system is provided. A design limit of -80 mm Hg for 15 minutes has been demonstrated. Normal operating pressure is -30 mm Hg. Provisions have been made to integrate the ergometer with the LBNP. The two systems have been designed to operate individually, separately, or simultaneously, and in either the vertical or horizontal mode. Development needs have been identified for future investigations. The major areas requiring further study are: generator design, weight reduction, material analysis, and flight version design.

LIST OF CONTRIBUTORS

<u>Name</u>	<u>Area of Contribution</u>
F. E. Riley	Project Direction
C. C. Cain	Physiology
A. L. Weitzmann	Design
K. B. Allen	Design
R. W. Blanchard	Design
S. W. Salat	Design
T. W. Macomber	Structure Analysis
D. W. Hayes	Dynamics Analysis
H. T. Fisher	Human Engineering
Consultant	
Daniel J. Feldman, M.D.	Director of Rehabilitation Service, Stanford Medical School, Stanford, California
Subcontract	
David Clark Company (D. Sears)	Fabrication of LBNP

AIR FORCE MEDICAL DIVISION MONITORS

Lt. Col. J. W. Ord
Maj. K. H. Cooper

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Section 1

INTRODUCTION

The Aerospace Medical Division, as a result of its concern for the possible debilitating effects of space flight, initiated the development of countermeasures. These devices are designed to diminish or prevent the deconditioning effects of weightlessness and other environmental factors. LMSC was directed to investigate and identify the possible effects of orbital flight stress factors, review existing conditioning devices, conduct an analysis of countermeasures, and then proceed with the development of selected countermeasures.

An orderly and comprehensive comparative countermeasure analysis was performed. Twelve candidates were selected for analysis and they were grouped into four categories due to the similarities of the physiological responses resulting from the application of the countermeasure. A recommendation was made that the optimum countermeasure system should be selected from two or more of the categories to insure different types of physiological responses. A countermeasure system incorporating both was considered most promising for further development and testing. The system selected employs a bicycle type ergometer, and a Lower Body Negative Pressure (LBNP) chamber.

In order to offset the restriction on body movements imposed by cramped quarters and the lessened workload found under zero-gravity conditions, exercise by means of an ergometer is considered sufficient to prevent muscular atrophy. The synthetic workload should also assist in maintaining work capacity. The advantages of bicycle ergometry are; availability of good baseline data, accurate assessment of work load, compact, and operation independent of spacecraft power.

The possible use of the LBNP as a means to counteract deconditioning and for provocative physiological testing has been demonstrated. Physiologic effects similar to those of head-up tilting are produced by the application of negative pressure to the lower body. The exposure of the lower half of the body to reduced pressure leads to an engorgement of the veins of the legs and the abdominal viscera, thereby counteracting blood pooling in the chest cavity and increased pressure in the left atrium. In this way the loss in blood volume due to diuresis stimulated by engorgement of the chest veins is inhibited.

A distinct advantage of the LBNP is that it lends itself to the same method of testing and validation in the ground laboratory as proposed for inflight provocative testing and use as a countermeasure.

The possibility of combining two countermeasure devices was investigated. This established the requirement to size the LBNP so that pedal type exercise could be performed. Interface specifications were made to ensure that the integration of the ergometer and the LBNP could proceed satisfactorily.

The design and development of the integrated Ergometer/LBNP took place in three versions. Each succeeding version after the initial version was improved by solving design problems uncovered during either LMSC in-house testing or the AMD evaluation program.

This report will summarize the individual technical tasks that were performed.

Results of LMSC testing will be presented and future development needs outlined. A preliminary plan for development of a flight prototype system is also discussed.

Section 2

TASK SUMMARY

The major objective of this project was to develop in successive order three versions of the integrated Ergometer/LBNP system. This section summarizes the analysis, design, fabrication, and testing conducted under the following specified technical tasks:

- o Task 1 - Design study for optimum countermeasures
- o Task 2 - Development of initial version of the integrated Ergometer/LBNP
- o Task 3 - Development of advanced version of the integrated Ergometer/LBNP
- o Task 4 - Development of final version of the integrated Ergometer/LBNP

2.1 TASK 1 SUMMARY

The initial effort of the design study for development of space-flight devices to diminish or prevent the deconditioning effect of weightlessness investigated:

- o Identification of the possible effects of orbital flight stress factors
- o Review of conditioning devices
- o Analysis of countermeasures
- o Preliminary design of selected countermeasures

2.1.1 Literature Review

A review of cardiovascular physiology under normo-gravic and hypo-gravic environment has been presented by McCally and Graveline,¹ including a discussion of important bed-rest studies of Dietrick, Whedon and Schorr.^{2,3}

First animals and then men were exposed to short-term weightlessness without any detectable cardiovascular abnormalities of importance. Reviews⁴ of the early space-flight experience on animals was reported by Cain,⁴ and Beisher.⁵ In V-2 and Aerobee rocket flights with monkeys and mice in this country and in similar rocket flights with dogs in the Soviet Union, no significant changes were noted in the electrocardiogram and blood pressure tracings during very short periods of weightlessness. Detailed reports on the early manned US flights produced no major cardiovascular problems.^{6,7} Data released in the popular press by NASA concerning Gemini 5 flight would indicate that Conrad and Cooper withstood the

stress of their eight day flight without any evidence of serious cardiovascular disturbances.

Even though actual space flights have produced no serious detectable cardiovascular effects, the lack of adequate controls and in-flight objective data raises a question, that must be answered on subsequent flights with adequate controls and experimental techniques. In essence this question involves the subliminal effects of the relatively short duration flights.

US Air Force and Navy laboratories have reported potentially serious cardiovascular abnormalities encountered in some of their water-immersion and bed-rest studies which are considered analogous to weightlessness.

Graybiel's group at the Naval School of Aviation Medicine in Pensacola reported postural hypotension when subjects were placed on a tilt table in the post-immersion periods.

Graveline at the Air Force School of Aerospace Medicine, San Antonio, reported his observations during his own seven-day immersion up to neck level. He, too, shows no significant cardiovascular changes while in the water, but hypotension occurred on the tilt table after immersion.

Benton⁹ and Beckman¹⁰ of the US Navy Acceleration Laboratory did immersion studies on nine subjects and reported no adverse effects except for one subject, in water for twenty three hours, who developed atrial tachycardia at the end of immersion, and became syncopal upon sitting upright.

Cardiovascular deconditioning during chair rest was reported by Lamb¹¹ in which six subjects showed manifestations of orthostatic intolerance after approximately four days. He concluded that complete physical inactivity over a short period of time, uncomplicated by the problems of weightlessness or simulated weightlessness, will cause adverse changes in circulatory dynamics leading to syncopal reactions or circulatory collapse upon testing. Lamb¹² concludes that cardiovascular deconditioning in the presence of normal transverse g force application, inactivity and immobilization has not proven that weightlessness has an adverse influence on the circulatory system.

It would perhaps be premature to attribute to weightlessness per se the physiologic responses observed in Shirra and Cooper following their respective first orbital flights. Several factors may be responsible including the amount of exercise, mobility, position of body and degree of dehydration. McCally and Graveline², Lamb¹² and Downey and Cain¹³ have thoroughly discussed water balance in the weightless environment and predicted the physiological effects of extended space flight. The excellent survey of chronic weightlessness¹⁴ by Wunder and the discussion of biophysical effects of weightlessness and its control¹⁵ have been used extensively by investigators to evaluate weightlessness countermeasures

and study techniques of their application.

The use of lower body negative pressure (LBNP) as a means to counteract deconditioning occurring when man is exposed to the weightless environment has received considerable attention by research workers at the USAF School of Aerospace Medicine (SAM), Brooks AFB, Texas. Stevens and Lamb¹⁶ have shown that application of negative pressures of -25 to -80 mmHg to the lower half of the supine body produces cardiovascular changes similar to venesection and upright tilting. The heart rate increases between 13 and 67 per cent; central venous pressure decreased by 3 to 6 mmHg; cardiac index falls by 20 to 42 percent and stroke volume decreases by 28 to 64 percent. They conclude that the physiologic changes induced by lower body negative pressure are secondary to redistribution of blood volume as a result of pooling in the pelvis and lower extremities.

Application of LBNP during the last three days of a four week period of bed-rest depleted the plasma volume and prevented orthostatic intolerance in a study involving 22 subjects¹⁷. The heart rate was much higher in response to a given "dose" of exercise at the time the plasma volume was decreased. This finding prompted the suggestion by members of the SAM research team that an ergometer should be integrated with the LBNP. In a later study involving 12 subjects, Stevens and others¹⁸ presented evidence that exposure to LBNP is capable not only of maintaining the plasma volume at baseline control levels but is also capable of preventing the orthostatic deconditioning that occurs during prolonged bed rest. Exposure of a chronically recumbent individual to intermittent LBNP during the time he would otherwise normally be standing, reproduces the hemodynamic changes that would occur in the erect position, thus activating many of the mechanisms that compensate for the effects of gravity. A number of compensatory mechanisms operate to offset the effects of gravity on man. This is quite apparent in the venous columns since the veins are more distensible than the arteries and the venous pressure in a foot vein is only a fraction of the pressure required to support the column of blood back to the heart level. A combination of mechanical forces for returning blood to the heart in the upright position in a normal g environment are brought into action by the application of LBNP in the deconditioned subject. Gilbert et al¹⁹ and Miller et al²⁰ of the SAM research team have suggested application of LBNP during prolonged space flight.

The information derived from the literature search was combined with data developed during the AF632A contractual effort to construct an evaluation matrix, Table 2-1. This matrix was used to isolate and examine the effects of weightlessness and other on-board stresses, and also the effectiveness of selected countermeasures, on specific physiological functions of the major body systems. The direction of change in each body system (dependent variable) is indicated in the cell corresponding to the independent variable. The independent variables include weightlessness, other on-board stresses and various countermeasures. Using the information presented in the matrix, it is possible to select a counter-

Table 2-1

EVALUATION MATRICES

WEIGHTLESSNESS EVALUATION MATRICES

INCREASE ↑
DECREASE ↓

A QUESTION MARK (?) INDICATES EFFECT OF STRESS FACTOR ON PHYSICAL INDEX UNKNOWN OR UNDETERMINED FOR THIS EVALUATION.

	CARDIOVASCULAR SYSTEM				RESPIRATORY SYSTEM				METABOLISM, SOLIDS, FLUIDS, ELECTROLYTES					BODY MASS MUSCULO-SKELETAL SYS.			CENTRAL NERVOUS SYS. & SPECIAL SENSES				
	BLOOD PRESSURE	HEART RATE	ORTHOSTATIC REFLEXES	CARDIAC OUTPUT	MINUTE VOLUME	O ₂ CONSUMPTION	CO ₂ PRODUCTION	VITAL CAPACITY	HEMATOCRIT	CIRCULATING PLASMA VOLUME	TOTAL BODY FLUIDS	METABOLIC COSTS	URINARY VOLUME	URINARY ELECTROLYTES	MUSCLE MASS	CALCIUM LOSS	INTERNAL HEAT PRODUCTION	ORIENTATION	VISUAL ATTRIBUTES	COGNITIVE FUNCTIONS	VESTIBULAR CLUES
SPACE FLIGHT STRESSES	PROLONGED WEIGHTLESSNESS	↓	↓	↓	↓	↓	↓	↓	↑	↓	↓	↓	?	?	↓	↑	↓	?	?	↓	
	CONFINEMENT AND RELATIVE INACTIVITY	↓	↓	↓	↓	↓	↓	?	↑	↓	↓	↓	↓	↓	↓	↓	↓	?	↓	↓	?
	TASK OVERLOADING	↑	↑	?	↑	↑	↑	?	?	?	↓	?	?	?	?	?	?	?	↑	↓	?
	ANXIETY STRESS	↑	↑	?	↑	↑	↑	?	↓	↑	↓	?	?	?	?	?	?	?	↑	↓	?
	THERMAL STRESS	↑	↑	?	↑	↑	↑	?	↑	↓	↓	↑	↓	?	?	?	↓	?	↓	?	?
COMBINED ENVIRONMENT	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
COUNTERMEASURES FOR SPACE-FLIGHT STRESSES	FLACK OR VALSALVA MANEUVERS	↑	↓	↑	↓	?	?	↑	↑	?	?	?	?	?	?	?	↑	↓	↓	↓	↓
	POSITIVE PRESSURE BREATHING	↑	↑	↑	↓	↑	↑	↑	↑	↓	?	↑	?	↓	?	?	↑	↑	↑	↑	?
	OCCCLUDING CUFFS - EXTREMITIES	↑	↑	↑	↓	?	?	?	↑	?	?	?	?	?	?	?	?	?	?	?	?
	ISOMETRIC & ISOTONIC EXERCISE	↑	↑	↑	↑	↑	↑	↑	↓	↑	↓	↑	↓	↓	↑	↓	↑	?	?	?	?
	LOWER BODY NEGATIVE PRESSURE	↑	↓	↑	↓	?	?	?	↑	?	?	?	?	?	?	?	?	?	?	?	?
	CERVICAL NEGATIVE OR POSITIVE PRESSURE	↑	↑	↑	↑	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
	LONG AXIS COMPRESSION STANDING & WALKING	↑	↑	↑	↑	↑	↑	?	↓	?	?	↑	↑	↓	↑	↓	↑	↑	↑	↑	?
	BODY SURFACE DIFFERENTIAL TEMPERATURE	↓	↑	↑	↑	↑	↑	↑	?	?	↓	↑	?	?	↑	?	↓	↑	?	?	?
	OSCILLATING LINEAR ACCELERATION	↑	↑	↑	↑	↑	↑	↑	↓	↑	?	?	?	?	↑	↓	↑	↓	?	?	↓
	RADIAL ACCELERATION	↑	↑	↑	↑	↑	↑	↑	↓	↑	↓	↑	↑	↑	?	↓	?	↓	↓	?	↓
	RESPIRATORY RESISTANCE POS.-NEG. INTRATHORACIC PRESSURE	↓	↑	↑	↑	↑	↑	↑	?	?	?	↑	?	?	?	?	?	?	?	?	?
	ELECTRICAL MUSCLE STIMULATION	↑	↑	?	↑	↑	↑	?	?	?	?	↑	?	?	?	?	?	?	?	?	?
	DRUGS	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?

measure system that promises to influence a specific function in opposition to weightlessness and other on-board stresses.

2.1.2 CANDIDATE COUNTERMEASURES REVIEW

The changes occurring in the physiological functions, when exposed to a gravity-free environment, are not very well known or understood. The absence of data on the influence of prolonged weightlessness on the organ systems of the body makes the selection of specific countermeasures to cancel out the undesirable effects extremely difficult. If the influence of the absence of a gravitational field and its role in the production of observed phenomena were thoroughly understood, the institution of appropriate countermeasures would be easier to establish. There are no means currently available for simulating prolonged weightlessness on earth. All other environmental factors, such as temperature, pressure, g-loading, isolation and confinement, may be manipulated and controlled on the ground for a determination of their effects on man, at least to a degree where reasonable extrapolations to space operations can be made.

A basic list of candidate countermeasures was stipulated for evaluation during the course of the study. All of these measures were considered, as well as others identified by LMSC as having potential value. A brief summary of the candidate countermeasures is contained in this section.

Due to the similarities of the physiological responses resulting from application of certain of the countermeasures, they have been grouped in four categories, as shown in Table 2-2.

Category One. Category One includes exercise, long axis compression and electrical muscle stimulation. These countermeasures have essentially the same general effect of producing muscular movement, stimulating blood flow and compression of the long bones of the body.

Category Two. Category Two includes devices operating by increased intrathoracic pressure, which decreases venous return. This group of countermeasures includes the Flack or Valsalva maneuver, resistance breathing and positive pressure breathing.

Category Three. Category Three countermeasures include measures designed to impede the venous return by damming back blood in the peripheral veins. Such measures are occlusive cuffs on the limbs, lower body negative pressure, vasodilation by differential surface temperatures, and the application of positive-negative pressures in the cervical region. Of these, much work has already been done on occlusive cuffs. (In 1932 Hamilton and Morgan reported this method effective in reducing venous return.) Lower body negative pressure has been used extensively by the research workers at SAM, Brooks Field Texas.

Category Four. Category Four includes devices that apply accelerative

Table 2-2
CANDIDATE COUNTERMEASURES ARRANGED BY SIMILAR CATEGORIES

Category One

- a. Exercise (Isotonic and Isometric)
- b. Long Axis Compression
- c. Electrical Muscle Stimulation

Category Two

- a. Flack or Valsalva Maneuver
- b. Respiratory Resistance
- c. Positive Pressure Breathing

Category Three

- a. Occlusive Limb Cuffs
- b. Lower Body Negative Pressure
- c. Body Surface Differential Temperature
- d. Cervical Positive-Negative Pressure

Category Four

- a. Oscillating Linear Acceleration
- b. Radial Acceleration

force to the body. The oscillating linear acceleration device (double trampoline) has been tested in the laboratory at Boeing, and found effective. Radial acceleration is known to be effective, but has many drawbacks when proposed for use in spacecraft.

2.1.3 COUNTERMEASURES ANALYSIS

The rationale used in the countermeasures evaluation was directed toward finding the candidate(s) that optimally counteract physiological functions influenced adversely by weightlessness by one or more of the following means:

1. Stimulate cardiovascular reflex mechanisms
2. Stimulate skeletal muscles
3. Stress skeletal function
4. Increase respiratory function
5. Assist in maintenance of normal bone metabolism
6. Maintain normal function of genital urinary and digestive systems

The various candidate countermeasures were examined to establish a rating. Consideration was given to the effectiveness of the countermeasures against all of the effects in various body systems. The countermeasures were also evaluated in terms of conventional criteria such as safety, power, weight, volume, etc. Each criterion was assigned a weight factor (W) which reflected its importance for the operational aspects of the countermeasure system as well as for the overall manned spacecraft system. In addition to the Effectiveness Rating (R) and (W), each criterion was assigned to a descriptive factor (D), which is a reflection of benefit-penalty relationship. In order to establish a numerical score for each countermeasure, two procedures were used. In one the product of DWR/1000 was used. In the second method, DW was normalized to range of 1 to 10 and then added to the Effectiveness Rating (R).

Results of this second analysis compared to the initial merit rating method shows the following ordering of countermeasures:

<u>DWR Product Method</u>			<u>DW Equiv. + R Method</u>		
<u>Rating</u>	<u>Countermeasure</u>	<u>Merit Value</u> <u>DWR/1000</u>	<u>Rating</u>	<u>Countermeasure</u>	<u>Merit Value</u>
1	Exercise	9.9	1	Exercise	15.7
2	LBNP	8.8	2	LBNP	15.1
3	Radial Accel.	6.0	3	Radial Accel.	14.4
4	Occl. Cuffs	5.8	4	Occl. Cuffs	12.0
5	Flack or Valsalva	5.2	5	Flack or Valsalva	12.0
6	Respiratory Resis	5.1	6	Respiratory Resis	11.0
7	Press. Breathing	4.7	7	Press. Breathing	11.3
8	Oscill. Accel.	3.9	8	Long Axis Compr.	10.9
9	Diff Temp	3.1	9	Oscill. Accel	10.3
10	Long Axis Compr.	3.0	10	Diff Temp	8.9
11	Cervical Press	1.2	11	Cervical Press.	6.2
12	Electr. Stimuli	1.0	12	Electr. Stimuli	6.1

This comparison demonstrates that there is good agreement in the two methods. The only disagreement occurs in the last five countermeasures. In each method, the first two choices are exercise and LBNP so they were chosen for further evaluation and testing.

Conclusion. The analysis of the countermeasure devices as to their predicted therapeutic value by weighing them against thirteen criteria each with an assigned descriptive factor, assumes that quantitative values can be selected for each. This is not always the case. Best judgment must also be used, and therefore, is subject to error. The analysis is perhaps most useful in demonstrating an approach for selection of the best countermeasure and its method of application. As more data becomes available, the relative ranking of their effectiveness "predicted therapeutic value" will change. As the development proceeds, the devices for applying the countermeasure may improve and the increased reliability would alter the descriptive factor. A final judgement factor must be used since the therapeutic value may be considered so important that penalties to the overall system would be accepted to obtain the protection. As a case in point, the greatest effectiveness rating has been assigned to radial acceleration, but manned spacecraft of the immediate future cannot accept the penalty of heavy, bulky, complex equipment. Therefore, radial acceleration employing a short radius arm on an internal centrifuge should not be considered as a countermeasure.

Selection of a countermeasure system should include two or more devices that counteract different kinds of physiological responses. Since the categories have been selected on the basis of different types of physiological responses, this makes it highly desirable to select countermeasure devices from different categories.

In Category One exercise offers the best promise and should be included in any countermeasure system.

Category Two countermeasure devices have been studied in the laboratory and their physiological responses are well documented in the literature. However, their effectiveness for counteracting cardiovascular deconditioning resulting from long exposure in the weightless environment have not been demonstrated. It is to be noted that the devices listed in Category Two would not be difficult to incorporate in a countermeasure system if their benefit should be demonstrated.

Lower body negative pressure in Category Three receives the highest merit rating and should be thoroughly evaluated. Occlusive limb cuffs have been considered by some workers and are presently under evaluation.

In Category Four, radial acceleration has been thoroughly studied in a 1 g environment, and though desirable, represents a tremendous penalty to the system. Oscillating linear acceleration, although supported enthusiastically by some workers, has not been demonstrated to be effective in the relatively small free "uncluttered" area in manned spacecraft of the

immediate future.

The subsystem analysis of the countermeasure devices indicates that exercise and lower body negative pressure merits considerations in any countermeasure system.

2.1.4 Preliminary Design of Selected Countermeasures

Preliminary specifications were established based on the requirements to provide an integrated system. Major considerations were:

- . Means for maintaining a pressure differential for the LBNP down to -40 mm Hg
- . Pressure relief device will be provided
- . Pressure forces will be measured and not exceed 70 kg at -50 mm Hg
- . Ergometer will be a rotary type and will be removable from the LBNP
- . Tachometer and wattmeter will be provided
- . Power output will be controlled between 80 and 400 watts regardless of rotation velocity of the pedal
- . Pedal rotation speed between 50 to 100 RPM will be obtained
- . The LBNP will be collapsible

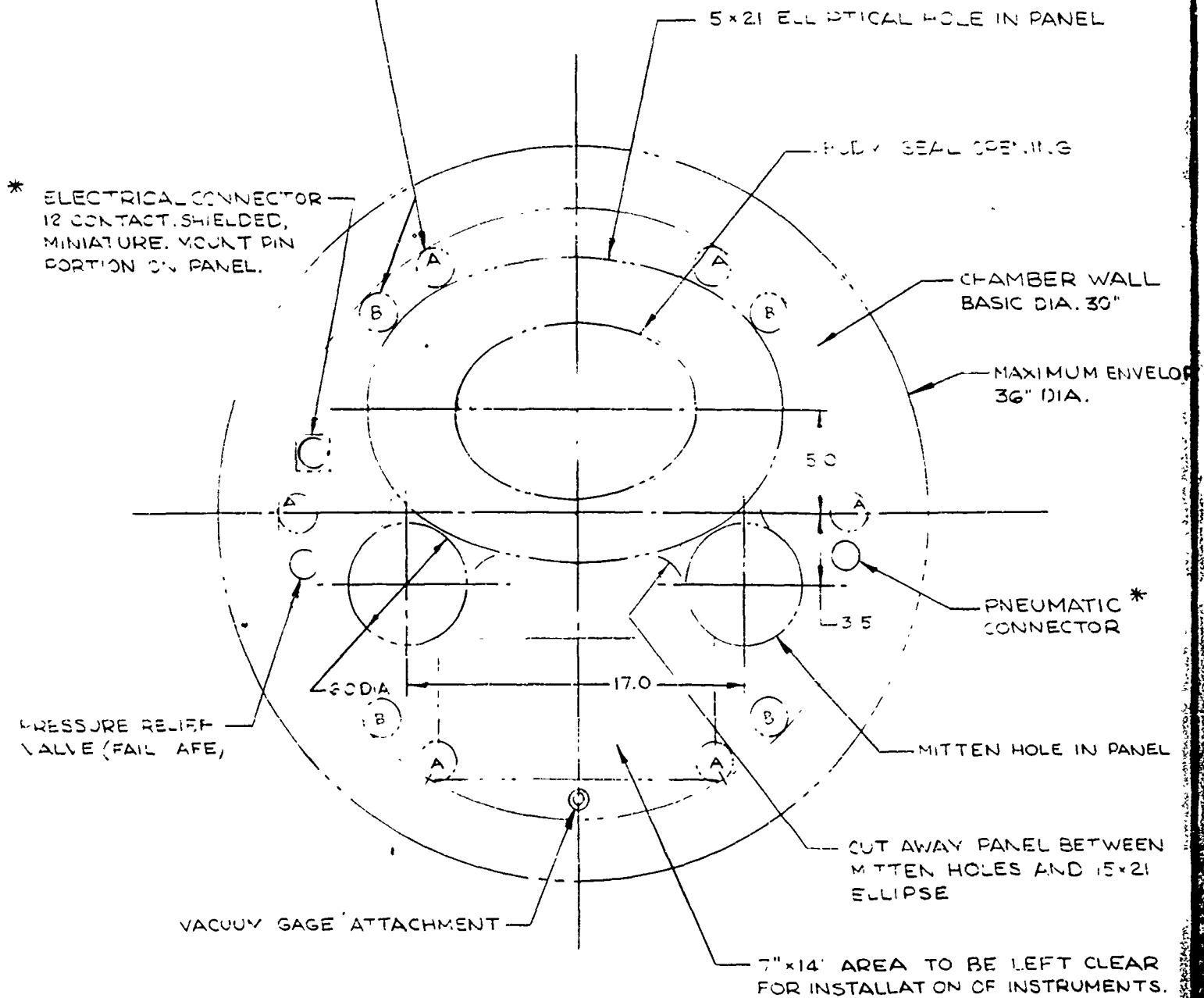
The major initial design problem was providing the David Clark Company with a preliminary interface specification drawing. After this step was accomplished and an engineering design meeting held between LMSC and the Clark Co., the design of the integrated Ergometer/LBNP was initiated. Fig. 2-1 illustrates the overall LBNP configuration required for integrating the ergometer.

2.2 TASK 2 SUMMARY

The second effort for developing the integrated Ergometer/LBNP resulted in the following:

- . Design and construction of the initial version
- . Test and evaluation of the initial version
- . Development of test program for the successive versions
- . Identification of the major problem areas
- . Preliminary design of the advanced version

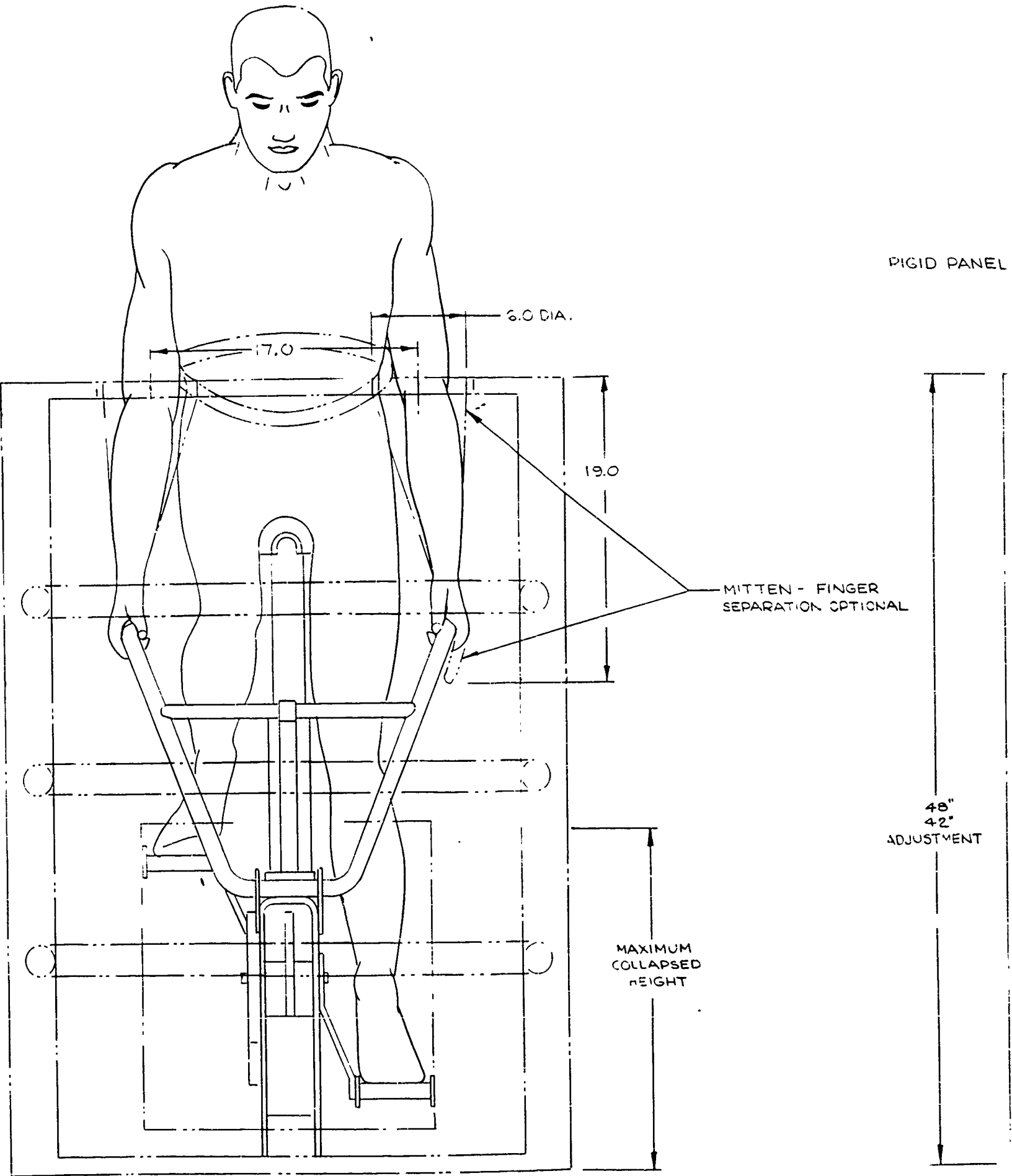
INFLATED FABRIC VERTICAL SUPPORTS
 INSIDE OF CHAMBER. 2 AT 'A' LOCATIONS,
 60° C-C OR 4 AT 'B' LOCATIONS, 90° C-C.
 IF RIGID SUPPORTS ARE USED, THEY
 SHOULD BE PLACED OUTSIDE OF THE CHAMBER.



* SIMILAR TO UNITS ON PRESSURE SUIT.

A

RIGID PANEL



B

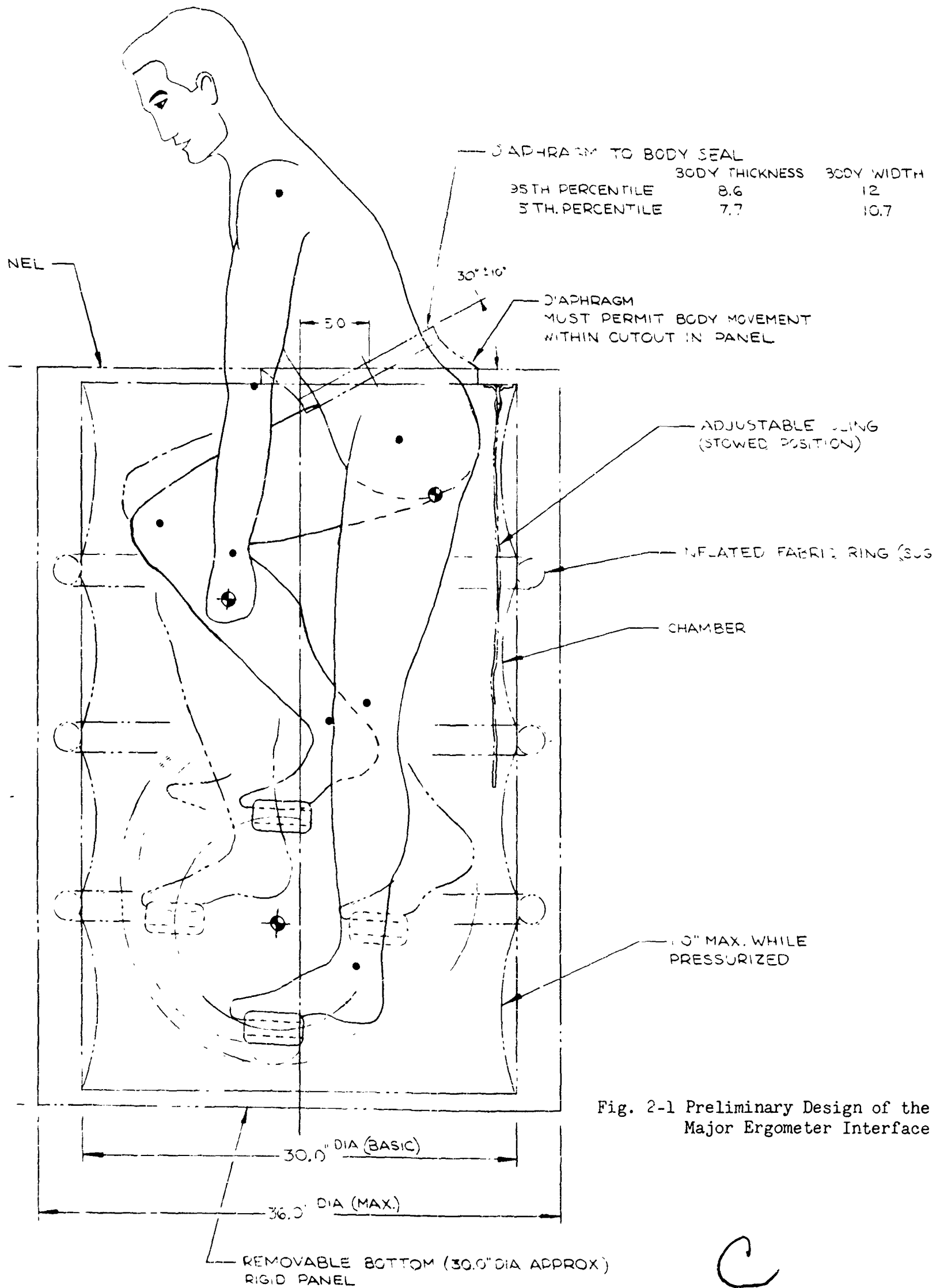


Fig. 2-1 Preliminary Design of the Major Ergometer Interface

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Preceding the fabrication of the initial version a laboratory study program was initiated to evaluate the generator and the solid-state electronic control system, which is used to maintain constant ergometer power output. A breadboard model of the ergometer mechanical system and the electronic control system was developed as illustrated in Figures 2-2 and 2-3. The mechanical system used standard bicycle parts wherever feasible but did employ a 25 to 1 gear ratio drive. The electronic control system employed available components. The breadboard model successfully demonstrated the capability of the electronic control system to maintain constant generator power output at a preselected value, regardless of changes in pedaling speed. In addition, the breadboard model demonstrated the practicality of using a standard off-the-shelf automotive generator.

The next step was the design, fabrication, and testing of the initial version. (See Figs. 2-4 and 2-5). Detail descriptions of both the LBNP and the Ergometer have been furnished in the Task reports. The following will be limited only to a discussion of design problems encountered.

The major problems in the development of the initial version were:

- . Smooth operation of the ergometer at high load and low RPM
- . Noise level of the ergometer
- o Waist seal of the LBNP during start up operation
- . Seal at operating pressures
- . Safety pressure valve operation
- . Possible collapse of the LBNP chamber

Design changes were initiated and discussed with AMD to correct the above problems. The major change to the ergometer was switching from a direct metal gear drive train to a poly-V belt drive system. The major change to the LBNP consisted of opposingly canting the longitudinal support members.

The test program established for the initial version and subsequently proposed for the successive version consisted of the following major steps:

- . Generator characteristics to be determined by a test which uses a dynamometer and gear reducer
- . Power required by ergometer alone (without generator) to be determined
- . Performance characteristics of ergometer (with generator) to be established

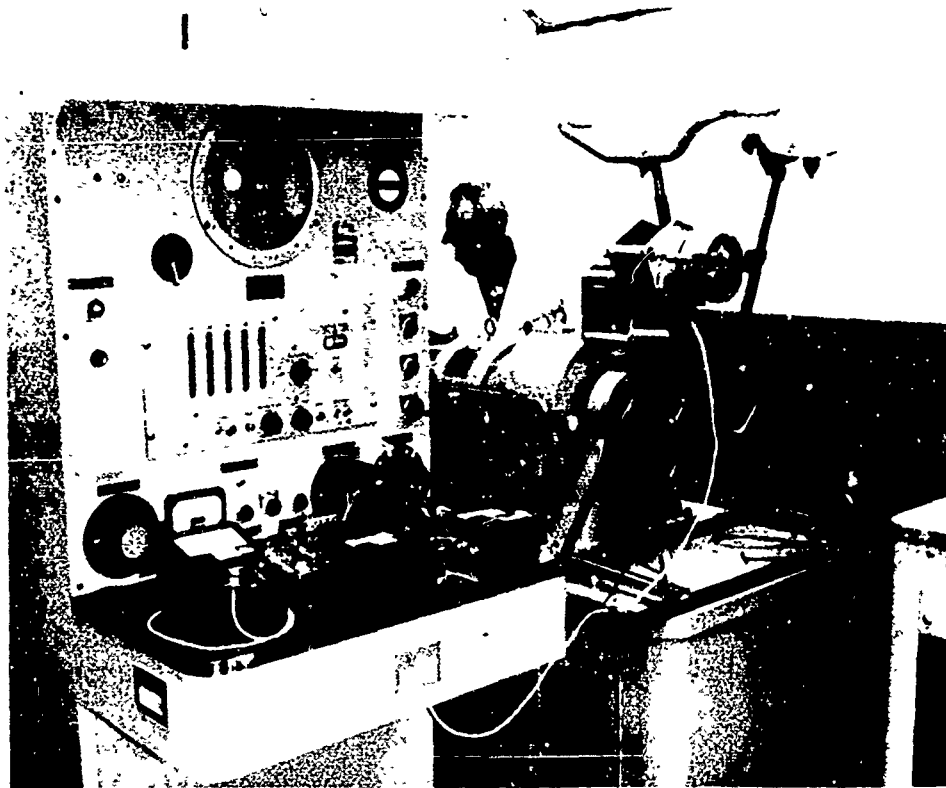


Fig. 2-2 Breadboard Model of the Ergometer
Being Calibrated by Means of a Dynamometer

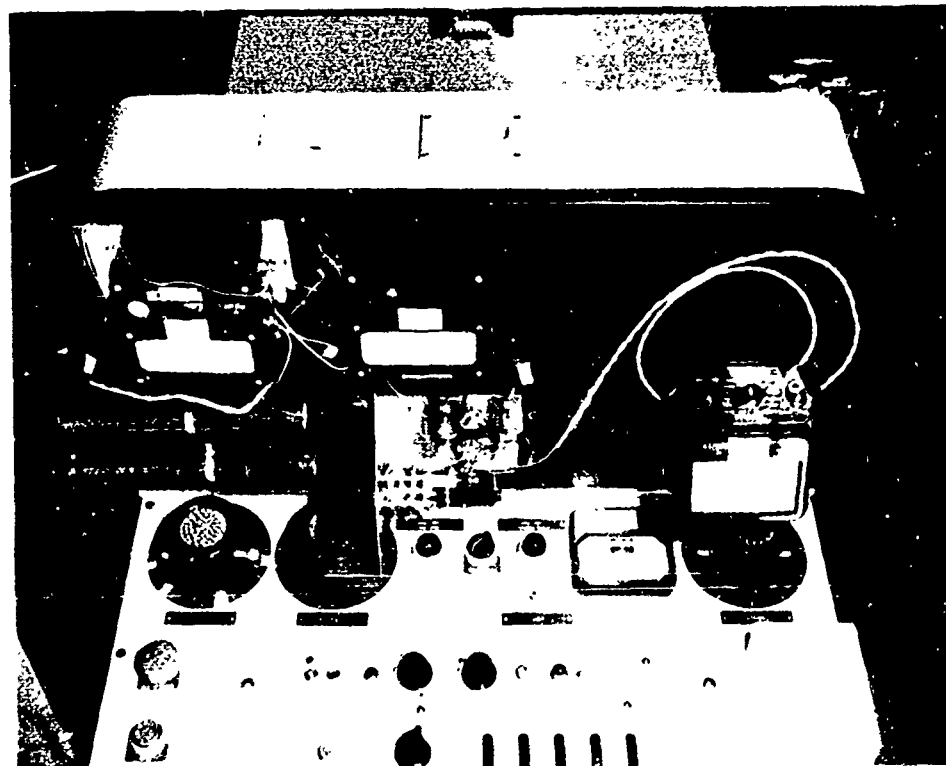


Fig. 2-3 Breadboard Model of the
Solid-State Electronic Control System

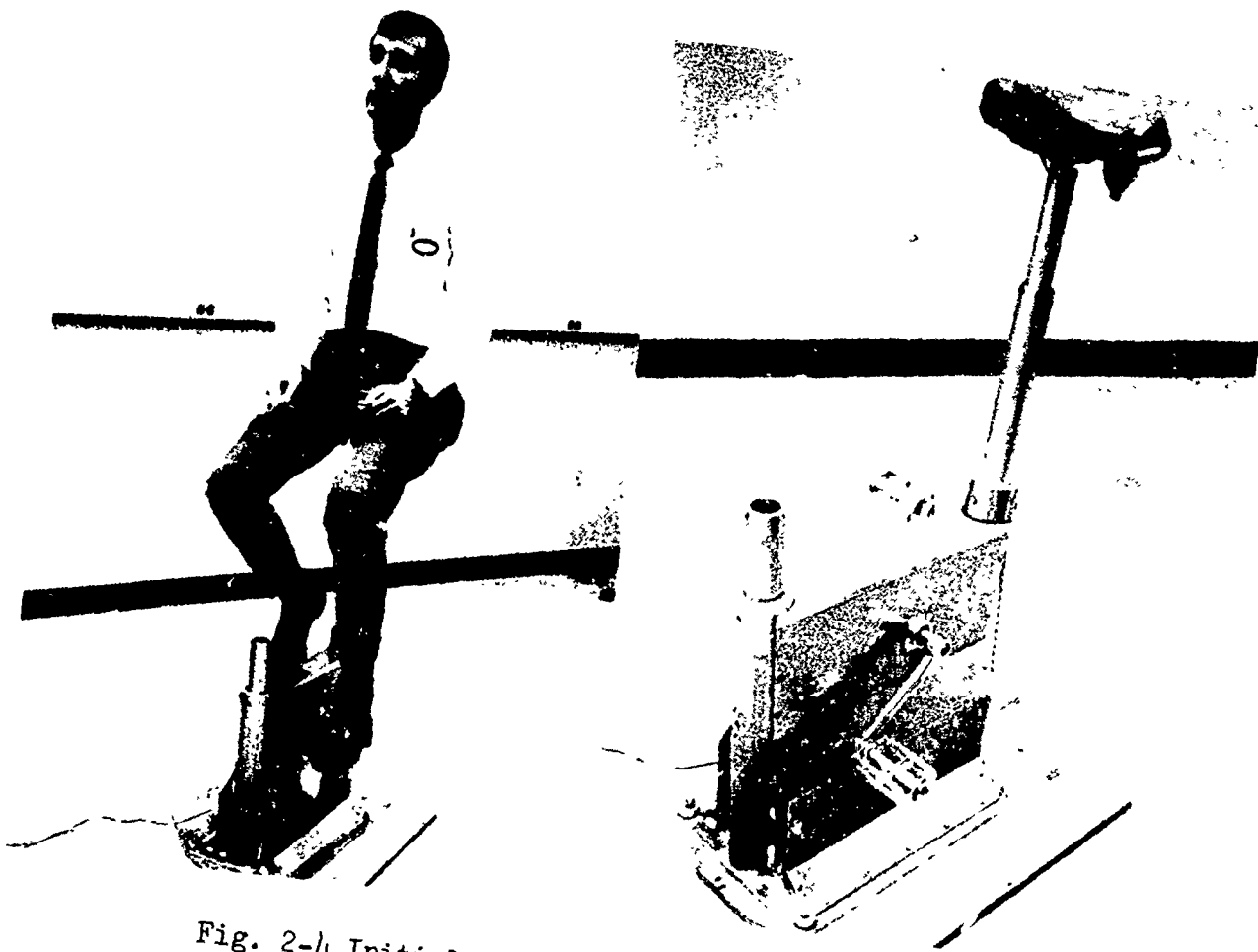


Fig. 2-4 Initial Version of the Ergometer

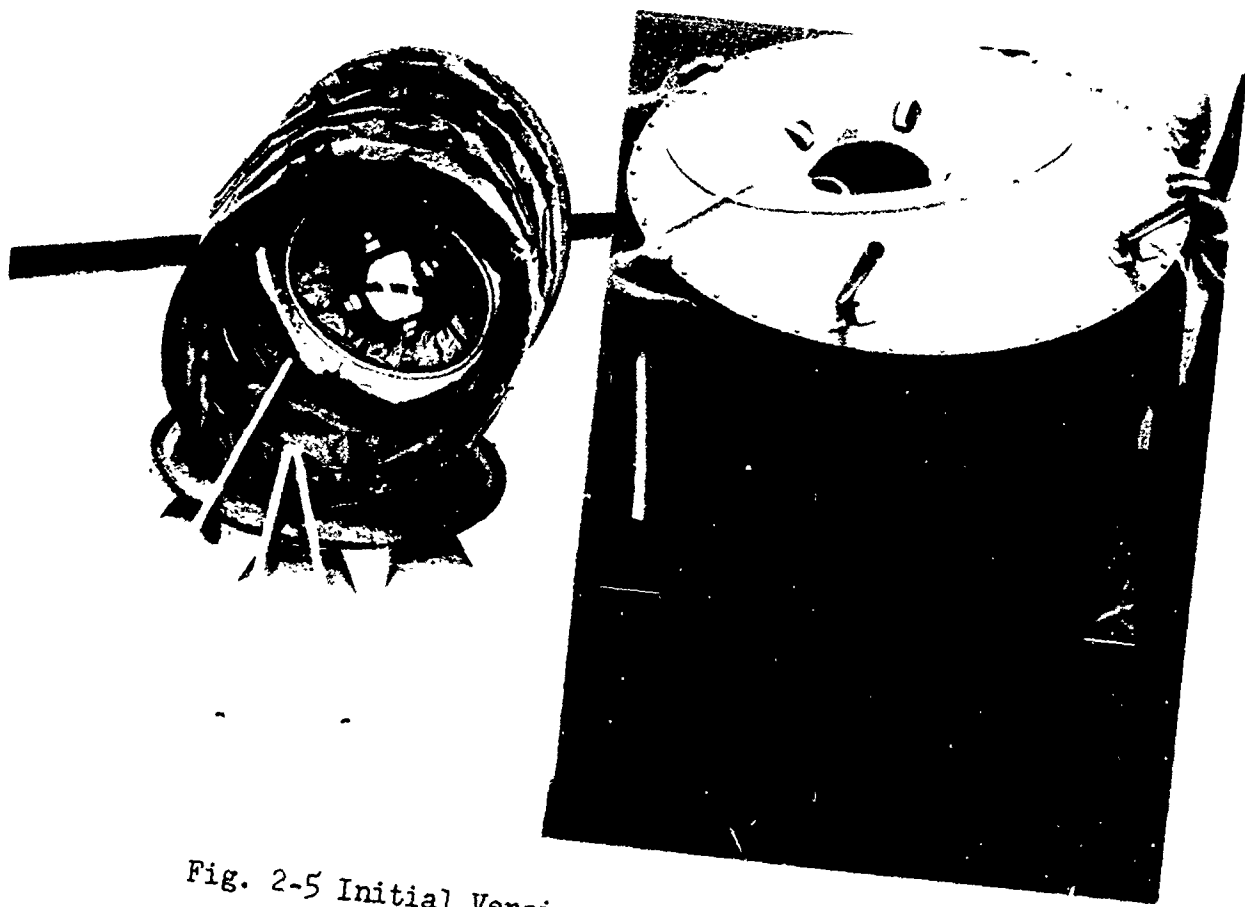


Fig. 2-5 Initial Version of the LBNP

2-15

LOCKHEED MISSILES & SPACE COMPANY

- . LBNP pressure test -80 mm Hg for 15 minutes (conducted by David Clark Co.)
- . LBNP force test on foot plate sensor
- . LBNP safety regulator checkout
- . Integrated Ergometer/LBNP checkout in vertical and horizontal positions

2.3 TASK 3 SUMMARY

The development of the advanced version integrated Ergometer/LBNP resulted in the following improvements:

- . Smooth operation of the ergometer at high load and low RPM (i.e., 60 RPM at 400 w)
- . Noise level reduction to 20 db over ambient by employing Poly-v Belts
- . A special belt was designed to take care of the discontinuity at the back and a seal designed for a 28" waist was developed to eliminate the seal problem
- . A "dead man" switch was provided in the pistol grips of the LBNP, and a subject operated ventilation flow valve that could be initiated with release of the operating switch was provided as well
- . The longitudinal support members in the LBNP were opposingly canted to prevent collapse
- . The longitudinal members were located in such a way as to provide maximum clearance for a pedaling subject
- . Toe clips were provided on the pedal assembly for clearance purposes
- . Power consuming and/or storage device attachment provisions were made available by supplying a kit to AMD
- . A material analysis was performed to determine the acceptability of the Poly-v belt material in manned spacecraft
- . A new type wattmeter utilizing the Hall Effect was installed in the control panel
- . Recording capability was provided at a rear connector on the control box

The advanced version retained all of the desirable features of the previous initial version and made changes or modifications where undesirable characteristics were identified. The advanced version clearly demonstrated the advantage of developing an improved version in successive order. Fig. 2-6 illustrates the advanced version of the Ergometer. Fig. 2-7 shows the LBNP.

The test program at LMSC followed the approved test plan and did not differ from that obtained during the initial version testing. Fig. 2-8 illustrates the integrated system checkout during the horizontal mode of operation.

During operation of the advanced version at AMD certain characteristics were noted that required improvement. All changes requested were incorporated in the final version. The following major recommendations were made by AMD for inclusion in the final version:

- . Improvement in limiting leakage
- . Comfort on the seat during vertical negative pressure operation
- . LBNP longitudinal rods stability
- . Waist seal leakage
- . Overpressure control

In addition to the major problems many small operational problems became evident which were resolved in the final version. These problems are very difficult to identify prior to actual use of equipment and point out the distinct advantage of successive development of prototype units.

2.4 TASK 4 SUMMARY

The major objective of task 4 was to develop the final version of the integrated Ergometer/LBNP and incorporate all the desirable features of the previous versions while improving the undesirable features. The final version is presently being evaluated at AMD. Preliminary results have indicated that LMSC has successfully developed a system that will prove useful in an evaluation program to be conducted by AMD.

The advanced version and the final version are very similar in respect to the ergometer mechanical and electrical system, and the LBNP basic chamber. Principle differences occurred in the control system for the LBNP. The following list illustrates some of the major features of the final version:

Ergometer

- c Anterior-post seat adjustment

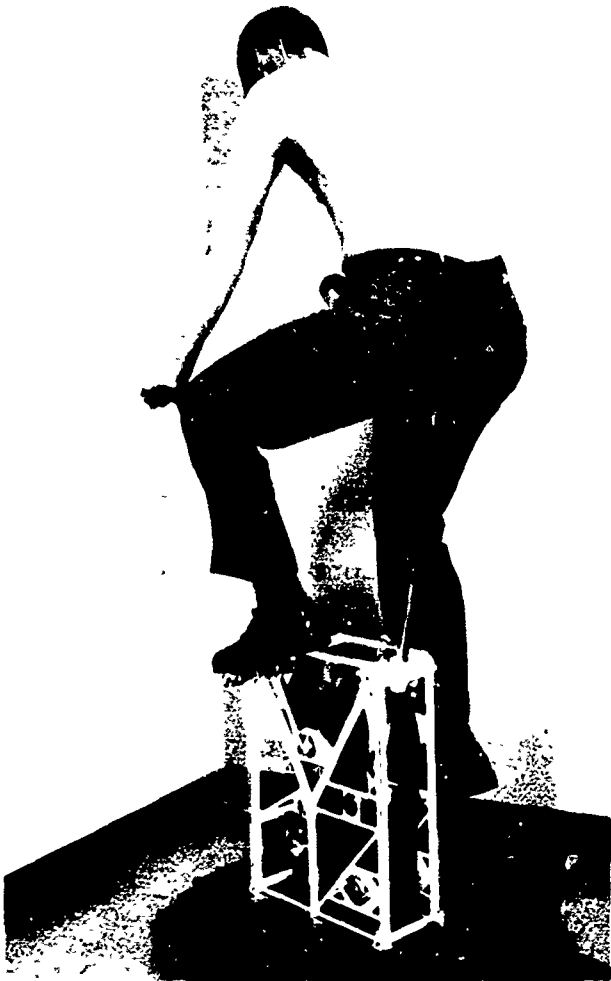


Fig. 2-6 Advanced Version of
the Ergometer

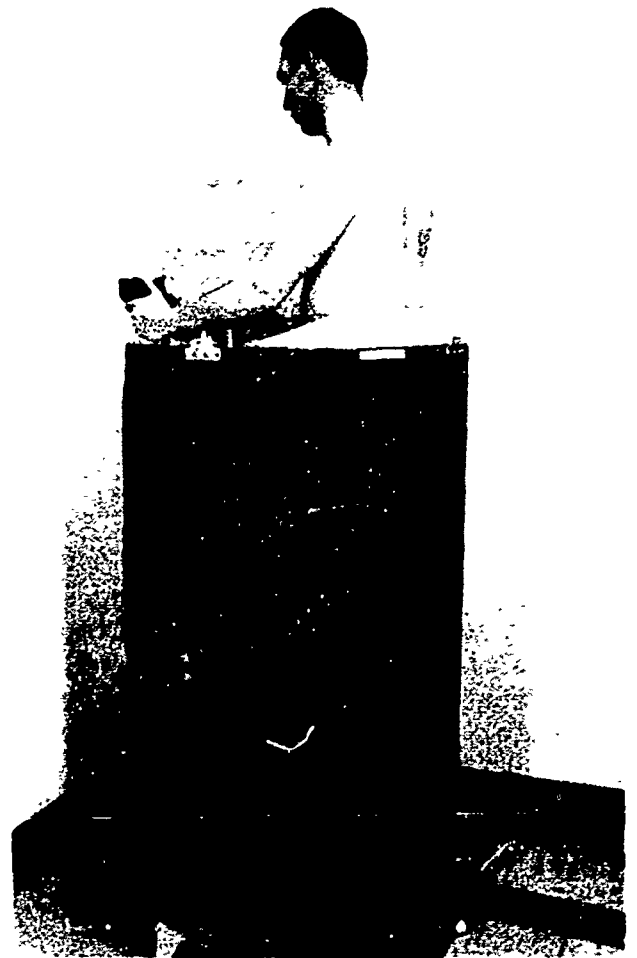
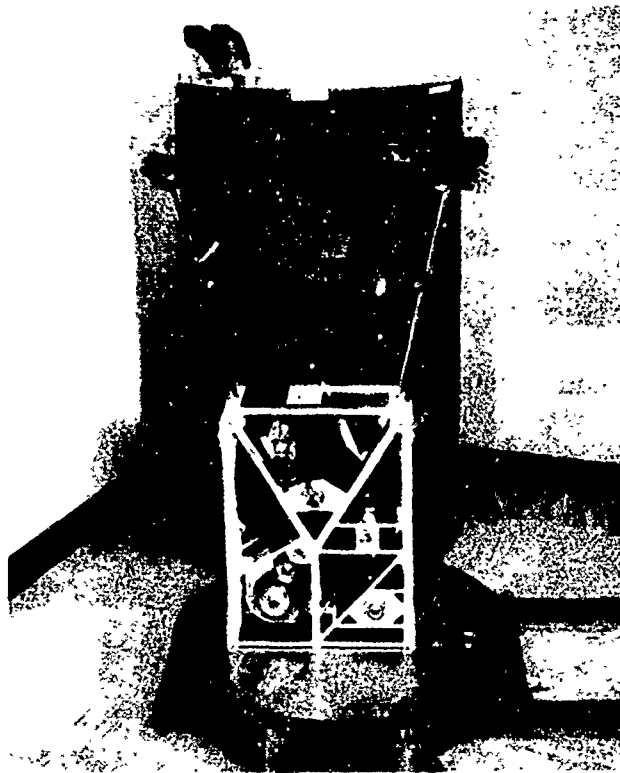
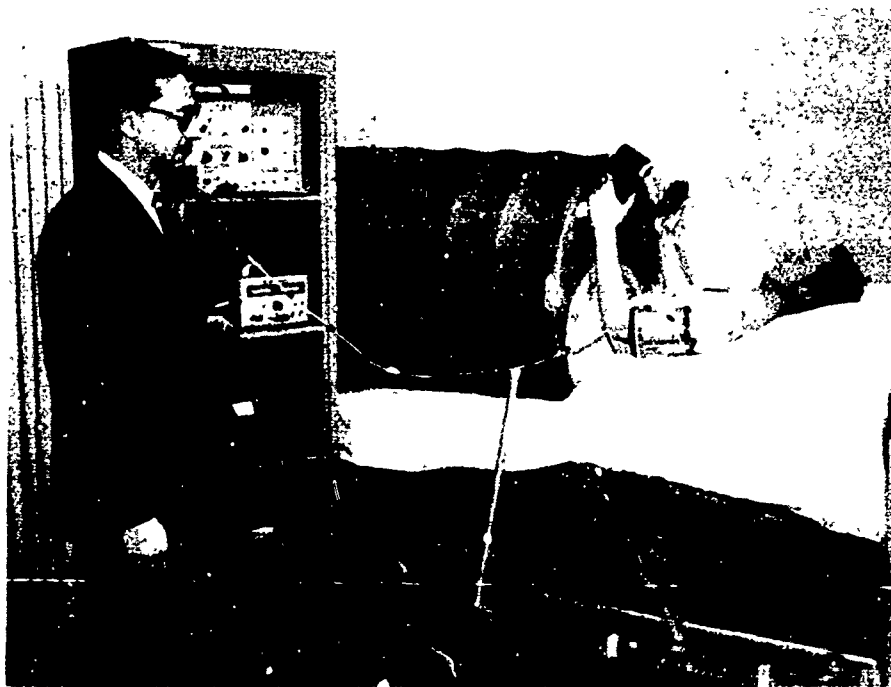


Fig. 2-7 Advanced Version of the
Lower Body Negative Pressure Device



Integrated System in Verticle Mode



System Checkout in Horizontal Mode

Fig. 2-8 Integrated Ergometer/LBNP System

- . Interchangeable seats (2) for comfort evaluation
- . Flywheels provided for angular momentum change (2)
- . Metal cover for ergometer
- . Suitable structure for stepping on top of ergometer
- . Toe clips on pedal assembly
- . Drive ratio 50 to 1
- . Tachometer and wattmeter recording capability
- . Weight 3 $\frac{1}{4}$ lb. (not incl. seat, handlebar, flywheel, or cover assembly)
- . Size 20.5 x 16 x 8 inches
- . Versatility - Vertical and horizontal mode
- . Smooth operation at high load, low RPM (i.e., 400 watts, 60 RPM)

LENP

- . Lower body chamber with rigid upper and lower panels
- . Circumferential tubes for side loads
- . Collapsible axial load supports
- . Two waist seals - 28" and 3 $\frac{1}{4}$ "
- . Bioinstrumentation - 19 separate leads
- . Generator electrical connection - 12 separate leads
- . Connectors on top and bottom for vacuum pressure indicator
- . Vacuum source connector on bottom panel
- . Double walled construction-restraint fabric and impervious gas barrier
- . Subject operated vacuum pump and relief valve
- . Overpressure control system consisting of a pressure sensitive switch and a relay - Reset feature at both the pistol grip and at the separate control switch - Vacuum motor automatically shut off

by overpressure condition - Ambient pressure restorable quickly through the vacuum line

- . Ventilation flow with a sliding panel adjustable for comfort
- . Elbow pads on top panel
- . A bioinstrumentation connection junction box with provisions for 6 shielded pairs is located on top panel.

Fig. 2-9 illustrates the final version of the LBNP system.

2.4.1 Final Version - Ergometer

The final version of the ergometer is similar to the advanced version. The final version employs a Poly-v drive consisting of 3 single endless rubber belts having a series of parallel V-ribs molded lengthwise around the inside circumference. A three stage train was required to accomplish the 50 to 1 drive ratio. A cam clutch was provided to enable the operator to "coast" upon completion of exercise. A spring loading system provides belt tension so that there is no slippage under the design load. A welded tubular steel frame provides the housing for bearings, shafts, pulleys, generator, and pedal assembly. The pedal assembly is made of lightweight steel components. Further weight saving can be effected by going to lightweight aluminum racing pedals. They were not available in time for inclusion on the final version. Conventional handlebars and seat are provided for operational use. An alternate seat is also provided to take care of the problem of comfort level when pulling a negative pressure during the vertical operating mode. This seat is a Vespa motorcycle saddle and provides a larger surface area.

Variation in the total angular momentum of the ergometer can be achieved by attaching flywheels at the generator shaft. Removal or adding the flywheel requires removal of the cover panel opposite to the generator housing. Six screws attached to Riv-nut fittings hold the panel in place. Provision has been made on the generator pulley to attach the flywheel. The generator can be taken out easily when the panel cover is removed. The spring loading system has been set and calibrated and requires no further adjustment. Increasing the tension would change the frictional losses while decreasing tension would cause belt slippage under load conditions. All bearings are sealed and no lubrication is required.

Electrical & Electronic System

The electrical and electronic system for the final version is identical to the one delivered with the advanced version and is interchangeable with that unit. Two banana plugs have been provided at the rear of the control chassis for attaching power consuming or storage devices to the ergometer. A 12 v light bulb for display purposes has been provided. It is recommended that the voltage level be maintained at 12 v or lower to prevent burning

- 1 Top Enclosure Plate - 1/8 AL
- 2 Waist Seal - Helenca ACS-3460
- 3 Suspenders- 5/8 White Nylon Webbing P-3314
- 4 Waist Seal Restr.-Sage Green Oxford Nylon P-728
- 5 Deutsch Conn. -DS07-19P-059 & 17064-19S-059
- 6 O To 3 Sq. In. Manual Vent - AL & Teflon
- 7 Stiffening Hoops 3/8 O.D. AL Tubing
- 8 Bottom Restraining Ring - AL Angle
- 9 Elbow Connector For Vacuum
- 10 Bottom Enclosure Plate - 1/8 AL
- 11 Press. Tap
- 12 Bulkhead Strap Bracket
- 13 Bulkhead Strap - 1" Wide Nylon Webbing P-2915
- 14 Bulkhead Strap Buckle
- 15 Draw Pull Latches
- 16 Legs
- 17 Sealing Gasket - 1/4 Thk. Rubber P-3113
- 18 Stanchion Retaining Balls
- 19 Vacuum Pump Electric Receptacle
- 20 Eyelets
- 21 Loop - 3/8 Tape P-600
- 22 Gas Tight Fabric - Neoprene Coated Oxford Nylon P-727
- 23 Foldable Stanchions - 1/2 O.D. Steel Tubing
- 24 Stiff. Hoop Retainers - 3/4 Bally Ribbon P-1387
- 25 Restraint Fabric - 8 Oz. Nylon Seat Pan P-733
- 26 Top Restraining Ring - AL Angle
- 27 Sealing Gasket - 1/8 Thk. Rubber P-3113
- 28 Lacing - P-428
- 29 Press. Gage - 2-1/2 In. 0-110 MM HG.
- 30 View Port - 6 In. Dia. Lexan
- 31 Hand Switch Case & Hand Grip --R.H.
- 32 Hand Grip --L.H.
- 33 Press. Tap
- 34 Pressure Control Switch Box
- 35 Waist Seal Hold Down Rings

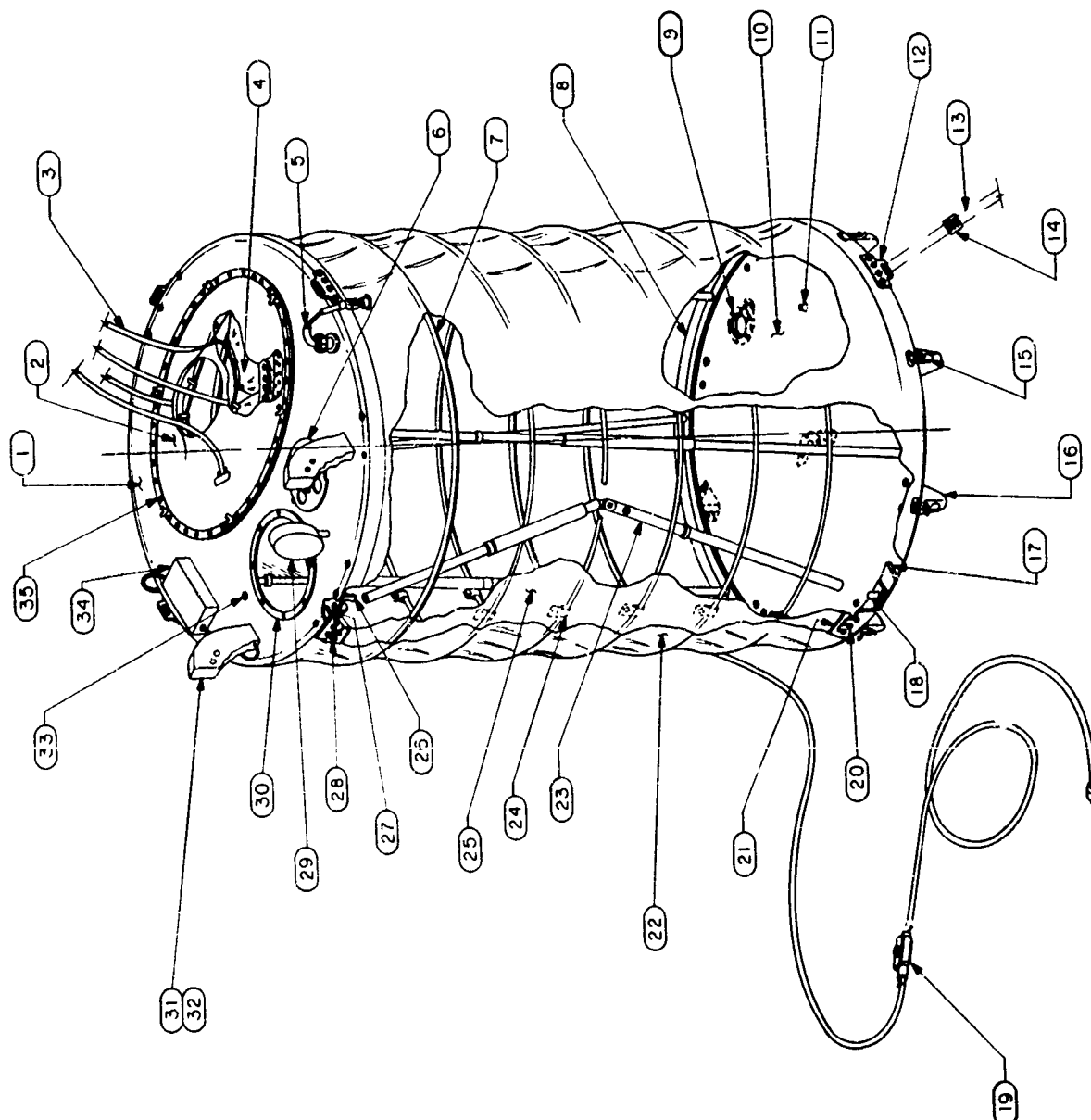


Fig.2-9Final Version of the LBNP

out the bulb.

The wattmeter mounted on the control unit displays mechanical input at 60 PRM. To arrive at a work load at another RPM it is necessary to refer to curves provided which give the relationship between mechanical input and electrical output at various RPM. Recording capabilities have been provided on the control unit.

2.4.2 Final Version - LBNP

The LBNP chamber was developed for LMSC by David Clark Co., Worcester, Massachusetts. The LBNP consists of a fabric cylinder with aluminum top and bottom panels. Circumferential rings are provided to carry the radial loads and collapsible metal tubes carry the axial loads. The longitudinal members can be removed and the chamber suspended by means of attachment fittings located on the upper and lower panels. Suspending the LBNP in such a manner requires attaching cables, or straps to the fittings and then securing the cables to suitable fixed structure.

A body seal has been provided that can be removed from the top panel. It is a one piece molded Helanca rubberized waist seal. Provisions have been provided for bioinstrumentation, electrical interface connection for the ergometer, subject operated vacuum pump and relief valve, an over-pressure control system consisting of a pressure sensitive switch and a relay, a bioinstrumentation connection junction box with provisions for 6 shielded pairs, and ventilation flow disc with variable openings.

The overall dimensions of the LBNP, 30 in. dia. and 48 in. height was dictated by the interface requirement of operating the ergometer within the chamber.

2.5 PERFORMANCE CONSIDERATIONS

All task reports and the initial and advanced version of the integrated system were delivered on the original schedule. The final version was delivered two weeks late for the convenience of the Air Force.

The most critical problem in meeting the schedule for this project was in securing the LBNP sufficiently ahead of time at LMSC in order to conduct an adequate integration and test program. This condition was critical because the subcontractor could not initiate procurement and fabrication of the next successive version until satisfactory results were obtained from the integration and test program.

2.6 DESIGN PROBLEMS

There were numerous design problems primarily concerned with operational use. Development of three versions in less than 8 months necessitated making certain design decisions that either restricted the space orientation,

or the completeness of the development cycle.

Since consideration was to be given to designing and fabricating an integrated system that would be flight oriented, early efforts were made concerning volume, weight, and power.

2.6.1 Ergometer Design Problems

The structural framework of the ergometer was designed for design load of $1\frac{1}{2}$ horsepower. This is well above the resistive load capability of the system i.e., approximately 1 horsepower. LMSC accepted this design limitation primarily because of the use environment-crew evaluation and because of the R&D nature of the project.

Once the desirable drive ratio was selected, based on considerations regarding initial starting torques, generator start-up, windage losses, etc., the pulley diameters, belt sizes, clutch design, and holddown fittings were only a matter of layout design engineering. Material selection of the many fittings, pulleys etc., became important because of the weight factor. A design decision was made that if a significant weight savings could be effected by going to a machining operation versus off-the-shelf purchase then the decision would favor the former. This philosophy influenced the design of the machined aluminum pulleys that form a major portion of the ergometer.

The selection of the generator to achieve the self-powered feature involved contacting over twenty-three companies. In each case the response was the same that there was not any off-the-shelf alternator that would meet the required specifications. Development times quoted by several suppliers indicated over 9 months which exceeded the requirements considerably. Ideally a brushless alternator would be used where the space cabin atmosphere might be 5 psi 100% O_2 . They are non-arcing which would reduce the explosion hazard. There are some brushless alternators available; however, their weight is 18 lb. It was decided that a standard automotive generator employing a slip ring would be used. It weighed 10 lbs. and easily met all power requirements. Since this item was off-the-shelf, it could be easily procured within the limited time schedule.

The control system was designed around the generator and controls the voltage. In a more space oriented design the control system would differ somewhat because it would be designed to control both the load and voltage.

These differences would be in the circuitry rather than in the components of the control system itself.

The majority of the design and development effort on the ergometer was concerned with producing an item that could be used in support of the proposed crew evaluation program.

2.6.2 LBNP Design Problems

The LBNP design was based on spaceflight environment consideration as well as laboratory use in the planned bed rest evaluation program. Paramount was the desire to keep the operational and stowed volume to a minimum. Initial design criteria established the requirement to provide a leak tight flexible collapsible chamber. Because of the nature of the evaluation program it was necessary to add certain design features that would permit the LBNP to be used in both the vertical and horizontal mode. Instrumentation recording capabilities were directed toward the ground based use rather than spaceflight applications.

Longitudinal support members were provided to take axial loads when using the LBNP in the vertical mode. In spaceflight these members could be removed and fore and aft tie-down fittings provided to anchor the lower and upper panels. The bottom panel was removable so that the ergometer could be easily added or removed.

Many of the design problems experienced during the development of the LBNP were occasioned by the use of the device under 1-g. It is believed that the spaceflight version of this unit could be greatly simplified. Further simplification could be achieved and considerable size reduction effected if the requirement to integrate the LBNP with the ergometer were removed.

A major problem in the development of the LBNP was creating an effective waist seal. Because of time constraint it was not feasible to investigate various techniques of effecting a negative seal. The molded seal developed by David Clark Co. is believed to be a logical choice. For the spaceflight version where individual measurements and custom fitting can be provided much better results are anticipated.

A conventional vacuum motor was used to create a continuous flow during operation of the LBNP. This provided cooling ventilation for the subject and eliminated any problems concerning leakage of the LBNP.

The overpressure control system evolved for the final version could be considered as adequate for any environment. Features are: override control by observer, automatic shut-off of vacuum, reset capability, and fast return to ambient conditions. The system consists of a pressure sensitive switch, and a relay. The pressure sensitive switch can be set for negative pressures ranging from -26 mm Hg to -200 mm Hg; however the structural limit of the LBNP chamber is -80 mm Hg.

Section 3
DEVELOPMENT NEEDS

As previously reported, one major area requiring further effort is the development of a generator specifically designed for spaceflight operation and specifically designed to meet the ergometer's requirements. Similar generators exist, as far as principle of operation is concerned; however, they do not meet the power or weight limitations of the space ergometer. In addition, LMSC has identified other major areas that require investigation. By continuing an R&D development effort for these two specific countermeasures, AMD will ensure the development of flight qualifiable space Ergometer/LBNP systems on a timely and economical basis.

The following areas are recommended for future investigations:

- . Material Analysis (determine compatibility of Ergometer/LBNP materials to allowable contaminant levels)
- . Weight reduction study and evaluation of restraint system
- . Generator design-space oriented
- . Control system for LBNP operation (vacuum source, etc.)
- . Flight design for Ergometer/LBNP and associated ground support equipment
- . Test and validation of Ergometer/LBNP under simulated Zero-g conditions

3.1 MATERIAL ANALYSIS

Materials used in the integrated Ergometer/LBNP system can be categorized as non-metallic and metallic. Investigation of the materials that are exposed to the atmosphere of a pressuring spacecraft and to reduced pressure or vacuum is critical. Non-metallic material requirements for the system include neoprene belts, special lubricants, sealant glue, bearings, etc. A material analysis should be conducted on selected critical components in atmospheres such as; O_2 -He, O_2 - N_2 , and 100% O . Contaminant levels after exposure to reduced pressures will be determined. Exposure at room ambient and elevated ($160^{\circ}F$) temperatures will be examined. Results of this analysis would permit specifying materials to be used in the flight version.

3.2 WEIGHT REDUCTION ANALYSIS

There are critical components in both the ergometer and the LBNP that could be subjected to stress/weight analysis. Trade-offs in drive ratio selection, design loads, truss analysis, double walled versus single walled LBNP, and operational equipment selection are some of the areas that should be investigated. Design curves should be developed that would support selection of design specifications for development of the flight version. Consideration would be given to spaceflight constraints and interface requirements. Interface problems between the spacecraft/equipment, equipment/operator, and equipment/operation should be determined and solutions offered. A space allocation study should be performed for both the operational and stowed positions.

3.3 GENERATOR DESIGN

The present Delco alternator is not considered suitable for space application because of its weight and potential fire hazard. A non-space oriented brushless alternator should be provided and a space oriented control system developed. After testing this system the specifications for the space oriented generator should be prepared. A space version should then be designed, fabricated and tested.

3.4 LBNP CONTROL SYSTEM

Identification and analysis of different techniques for controlling the differential pressure, including a method of cycling the pressure should be conducted. The major problem is the trade-off between open and closed systems. Consideration should be given to providing a completely self-contained system under direct control by the crewman.

3.5 FLIGHT SYSTEM DESIGN

The flight system of the Ergometer/LBNP will differ considerably from the final version developed for the crew evaluation at AMD. The exercise profile to be conducted in flight will establish the requirements. Current profiles indicate that an exercising crewman will not exceed a maximum work load of 300 watts, and will not be subjected to negative pressures greater than -30 mm Hg. These two design criteria alone will have a direct effect on the flight design from space and weight standpoints.

Methods of body orientation on the ergometer under weightlessness conditions can differ widely from ground based orientation. Examples of this are the possibility of eliminating the seat assembly and the handlebars and replacing these with handholds affixed to the cabin walls and a restraint strap that prevents sideways displacement. The end product of this task would be design layouts suitable for initiating the detail engineering design phase.

3.6 ZERO-g INVESTIGATIONS

Using the final version of the ergometer, a water immersion test should be initiated to determine the most efficient method of body orientation and body attachment during operation of the ergometer. This test would provide an early insight into the possibility of eliminating seats and handlebars and would assist in development of adequate restraint systems. Such early testing would greatly expedite testing under the simulated zero-g flight testing using the KC-135 aircraft at WADD.

3.7 OTHER APPLICATIONS FOR THE LBNP

The LBNP in its operational position requires considerable volume. However inherent in its large volume and general characteristics is the possibility to develop dual or multiple applications. A cursory examination of extra volumetric applications for a device such as the LBNP indicated such uses as: space shower, body volume measurements, hydrodynamic stimulation, EVA storage transfer, portable emergency airlock, controlled thermal environment, and emergency rescue garment. A feasibility study is proposed to examine such applications from a design standpoint. This study would take advantage of current AMD efforts regarding emergency rescue techniques, etc.

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13 ABSTRACT The object of the program was to provide prototype equipment for use by the USAF in laboratory studies of physiological deconditioning similar to that which results from space flight. Three successive versions of an integrated Ergometer/Lower Body Negative Pressure (LBNP) System were delivered to AMD. The ergometer consists of a self-powered bicycle type unit with a solid-state electronic control system to maintain constant generator output regardless of pedal rotation speed. Recording capabilities are provided for a tachometer, and a wattmeter. Provisions are made to attach power consuming or power storage devices to the ergometer. Work loads up to one horsepower can be accommodated. The ergometer was calibrated using a dynamometer and speed reducer. The LBNP chamber is fully collapsible and employs circumferential rings to support the side loads. For ground applications longitudinal support members are used to carry the axial loads. The waist seal is a single molded unit and is removable from the chamber. The chamber has provisions for 19 leads of bioinstrumentation. A fail-safe overpressure control system is provided. A design limit of - 80 mm Hg for 15 minutes has been demonstrated. Normal operating pressure is - 30 mm Hg. Provisions have been made to integrate the ergometer with the LBNP. The two systems have been designed to be operated individually, separately, or simultaneously, and in either the vertical or horizontal mode. Development needs have been identified for future investigations. The major areas requiring further study are; generator design, weight reduction, material analysis, and flight version design.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

INSTRUCTIONS

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