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DEVELOPMENT OF AN INTERNAL RESTRAINT SYSTEM FOR AN INTEGRATED RESTRAINT-PRESSURE SUIT SYSTEM

by R. S. Mazy, T. E. Mattingly, J. W. Felder Jr.
and C. F. Lombard

Prepared by
NORTHROP SPACE LABORATORIES
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FOREWORD

This report describes the technical tasks performed in the Development Of An Internal Restraint System For An Integrated Restraint Pressure Suit System. This work was sponsored by the NASA Ames Research Center Under Contract NAS2-2868, with E. Gene Lyman serving as Technical Monitor.

This study was performed between 7 June 1965 and 28 June 1966 by Northrop Space Laboratories, Hawthorne, California. Dr. C. F. Lombard was Program Manager.

Technical assistance to this program was provided by Leonard Christian, Ester Cook and Annetto D'Aquila of the Biodynamics Laboratory, Northrop Space Laboratories.

Northrop Space Laboratories has assigned document control number NSL 66-116 to this report.

ABSTRACT

The research and development leading to and including the fabrication of a working laboratory model of an internal restraint system for use in an Integrated Pressure Suit System is presented in this report. The system provides acceleration protection and thermal control by means of fluid-filled bladders. The thermal transport system is designed to remove at least 2,500 Btu/hr metabolic heat from the occupant. Results of studies conducted to determine the physical loads imposed on the restraint system under acceleration fields of $\pm 30\ G_x$; $+20\ G_z$; $-10\ G_z$ and $\pm 15\ G_y$ are included.

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INTRODUCTION

Increasing requirements for protection of astronauts and pilots in high performance aerospace vehicles points out the need for providing a better means of protection in high mechanical and thermal stress environments. The development of an internal restraint system for use in an integrated pressure suit-restraint harness system is another step towards meeting these requirements. This report describes the investigation, design, testing and fabrication necessary to develop a working laboratory model of the Internal Restraint System.

The Internal Restraint System is composed of a liquid filled garment system or garment and a separate auxiliary system. The garment is worn under the Integrated Restraint Pressure Suit System and contains two subsystems, the cooling system and the restraint system. The auxiliary system provides temperature control and a means of varying the volume and pressure of the Internal Restraint System. It is composed of a pump, heat exchanger, refrigeration system, heater, reservoir and the necessary controls to regulate the coolant system temperature. It is designed to circulate the fluid of the coolant system at a continuous one gallon per minute flow at any selected temperature from 35° to 85° F.

1.0 INVESTIGATION

A literature survey and review of pertinent systems was completed to determine requirements for an internal restraint system that would provide both acceleration protection and thermal transport. Functional requirements established as primary objectives were (1) support and restraint during impact acceleration, (2) support and restraint during maneuvering and vibration acceleration, and (3) removal of metabolic heat (thermal transport). Various methods of satisfying these requirements were explored and the results of this effort is presented in the following paragraphs.

1.1 SUPPORT AND RESTRAINT REQUIREMENTS

Based on NSL's experience and the literature survey, the following requirements for an efficient and serviceable support-restraint system were realized.

1. Comfortably support and restrain a crew member during normal operation without interfering with task performance.
2. Attenuate vibration amplitudes at various frequencies to make them tolerable or non-interfering.
3. Provide protection against long duration acceleration associated with large velocity changes.
4. Provide a high degree of protection during impact accelerations.
5. Be compatible with other systems and mission requirements.

1.1.1 Comfort

Comfort is interpreted in the physical sense to mean that no physical discomfort will be imposed by pressure points, orientation, or distortion of body segments, etc. This requires good environmental control, proper sizing, load distribution, and orientation to mechanical force fields.

1.1.2 Vibration

Vibration, especially during launch and perhaps during phases of glide reentry, requires some attenuation to protect the crew members. This attenuation may present problems. Coermann (1) in vibrating human subjects $\pm G_z$ in the supine position showed that the soft tissue complexes, such as the abdomino-thorax system, have a resonant frequency of about 3 cps and that restraint of this system shifts the frequency response upward to about 7 cps. Later, Coermann (2) points out that restraint of the soft abdomino-thorax system, to avoid excessive organ displacement and rupture of ligaments due to hard impacts, will result in a higher transmitted acceleration. Thus with vibration input and restraint for impact such as with a seated subject, the vibrational accelerations in the z axis are increased at the head. This rather defines the opposite sides of the problem of comfort during vibration versus survival during impact. The view of Coermann (2) that: "Since subjective tolerance to sinusoidal vibration is also due to excessive tissue displacement and head acceleration, it can be expected that any protective measure which improves the tolerance to vibration will also improve the tolerance to impact," is considered to be too broad and even conflicts with his own observations.

Vibration in the transverse direction ($\pm G_x$, $\pm G_y$), as shown in reference 3, has been studied using human subjects to a limited degree and then with limited areas of force input, such as the feet and the seat. This type of input gives rise to transverse standing waves with nodal points. What the influence of greater areas of contact of the forcing input will have upon the tolerance levels will depend upon many factors, as shown by Roman (4). Fraser (5) was concerned with the performance of crew members under vibrational environment and found decreased tracking performance related primarily to the amplitude of vibration modified by a fractional exponent of frequency.

This brief review of the effects of vibration indicates that attenuation of vibration for comfort and for task performance will be necessary depending upon the vibrational environment. However, any attenuation should be considered as possibly non-desirable during impact and should be fully evaluated during suit testing for its possible amplifying effect of G loads on tolerance and survival.

1.1.3 Acceleration, Long Duration

The area of long duration accelerations (accelerations longer than 0.3 seconds) is covered by many reviews in general, but specific new areas of interest are generated by the potential glide reentry of space vehicles as discussed by Thompson (6). Under certain desirable reentry angles, a pilot in a rather conventional seated arrangement might be subjected to acceleration loads which would have vector components up to +6 G_z and -9 G_x lasting for many seconds. Creer (7) conducted tests on the centrifuge in a simulated reentry maneuver and summarized: "tests indicated that a pilot could adequately control the simulated entry vehicle while immersed in a 14 G 'eyeballs-in' acceleration field for two minutes," but he also noted some reduction in the tracking performance in the 'eyeballs-out' orientation. In these studies, the suit was especially designed to provide essentially full support and restraint even to the facial tissues. This would indicate equal area coverage may be required in any suit-restraint-support system. Probably anti-g suit provisions will need to be made to combat the $+G_z$ vector component of such a reentry acceleration profile. Many problems of integration of various components of the suit-restraint-support and life support systems remain to be resolved for the best task performance under long term acceleration.

1.1.4 Acceleration, Impact

Tolerance and survival of the human to impact accelerations are items of even greater concern to designers of manned aerospace vehicles, e.g., during reentry and landing of space capsules, the onset rate to maximum G and the possible orientation to the force vector(s) are factors which may present severe design requirements. If the practical parameters of 1,000 G/sec onset to 20 G max are given for man while the vehicle experiences 3,000 G/sec onset to 30 G then there must be provided an attenuator device which will require space within the vehicle. However, the problem of orientation of the crew members to any one of a variety of impact loads, which may be repeated, poses the question as to the containment and also the question: what happens when the design limits are exceeded and the attenuator "bottoms out?" Perhaps through better containment and orientation higher impact can be tolerated and survived.

Snyder (8), in a recent publication has reported data on 137 cases of individuals who have survived extremely abrupt impacts in free-falls. Although he reports a lack of information concerning pathology incurred in internal organs (survival), he states in summary: "It has been shown that humans have survived impact forces considerably greater than those previously believed tolerable." From the analysis of these free-fall impacts and the rather extensive literature review, Snyder was seeking "clues or patterns which can open new approaches to the protection of the body during high decelerative forces."

Mayo (9), in reviewing NASA impact work and plans, points to the "normal" operation from the standpoint of impact as well as the other loads; and the second division of emphasis having "to do with what happens when things go bad." He states, "the problem is to discover what the man can tolerate in order to save his life. In this instance we have no holds barred, so to speak, in exploring the maximum capabilities of saving a man."

Stapp (10), using men as subjects to establish tolerance limits and animals (chimpanzees and hogs) to establish survival limits, found that both orientation and containment, in addition to the deceleration profiles, were very important factors in establishing these limits. In the hog experiments, the survival subjects were sacrificed and the visceral pathology which was incurred was determined. May questions remain since (a) the orientations were limited to forward, rearward and footward presentation to the decelerative force, (b) the support was non-contoured to the hog, and (c) the restraints were limited to aircraft-type restraints including leg straps. However, this pioneer work definitely shows a correlation between increased survival limits and improved support-restraint systems.

The reports and opinions of the above referenced authors 8, 9, 10, show the need for more concise information. Lombard (11, 12, 13) has shown not only the importance of considering the overall spectrum of tolerance and survival limits, but also the details of the areas of anatomical and physiological "injury" as related to orientation and containment. Stapp (14) has shown the importance of the details of containment as related to the survival of chimpanzees during exposure to $\pm G_x$ up to 100 G at onset rates as high as 36,000 G/sec. Lombard (15) has shown further details on the correlation of injury/survival with high impact loads and rates of onset; and containment and orientation. Significant findings were:

a. Animals exposed right or left side forward ($\pm G_y$) are in an equally good if not better orientation for survival than those in a forward or rearward facing ($\pm G_x$) orientation but only if they are in a fully contoured support-restraint system.

b. Restraint and support of the head is necessary but must be done with careful consideration of several mechanisms of injury of the central nervous system. The head must be restrained at a right angle to the spinal axis, but not tightly, and some padding must be provided to prevent cerebral damage.

c. The problem of support-restraint for the thorax and abdomen appears to be again one of contouring. Using a flat support and backward facing ($+G_x$), eight out of nine (guinea pig) subjects were fatally injured as opposed to 1 out of 33 with the contoured support. The 33 tests included longitudinal contouring in the neck area versus non-contouring. The pathology incurred while using the flat support in the $+G_x$ orientation was rupture of the stomach, tearing of mesenteries, hemorrhagic areas in the lungs, and hemorrhage over various surface areas of the brain, but more frequently on the ventral surface.

d. The survival of guinea pigs to impact accelerations can be greatly increased by proper orientation and containment and is much higher than reported by Richmond (16).

1.1.5 Compatibility

Compatibility of the support-restraint system with other systems and mission requirements can be achieved only by very careful study of individual component interfaces of each system and the integrated performance of all components, including the crew member, to meet the mission requirements. Each potential component of the support-restraint-suit-restraint system and internal environmental control system was examined to determine any common properties of potential components which can be utilized to serve more than one purpose or function, such as the suit also serving as a thermal transport garment. This required a cross check analysis to determine the most efficient integration of materials to provide for support-restraint and thermal transport without interfering with comfort of the wearer and his mobility.

1.2 SUPPORT-RESTRAINT SYSTEM

Information was compiled on the physical loads imposed on the internal restraint system by various body masses of a 95th percentile man under acceleration fields of $\pm 30G_x$; $+20G_z$; and $\pm 15G_y$, e.g., load vectors for body components shown in ASD TR-61-546 (17), the work of Dempsey (18), and Vykukal (19).

As discussed previously, contouring certain areas with padding is essential for tolerance and survival during impact in $\pm G_x$ and $\pm G_y$ orientations and attenuation of vibration is essential for comfort and task performance. To meet both of these requirements with minimal mass and volume and to consider the sizing problem as well, pad systems were evaluated for use with the specified suit.

Fluid filled bladders in support-restraint systems, especially those with limit-stretch, have been advocated by C. F. Lombard since his presentation on this subject to Major Stan White and his staff at NASA/MSC Langley Field early in 1959. Subsequently, Lombard (20), under contract with the Air Force, showed the potential of this system for protection during impact by in vitro experiments using a 1/5 scale manikin. In company sponsored research at NSL, Thiede (21) showed, by in vivo experiments using guinea pigs, that the fluid-filled limit-stretch bladder principle can be used for protection against impact in the $\pm G_x$ and $\pm G_y$ orientations with some benefits in the $+G_z$ orientation. Thiede showed that blast injuries were produced in subjects fully immersed in a water filled container during impact deceleration.

Consequently, it was determined that properly constructed fluid filled bladders could be used in a support-restraint system to provide contouring and sizing for impact protection as well as some attenuation of force. These same bladders or fluid-filled devices could be used for the liquid thermal transport system.

1.3 THERMAL TRANSPORT SYSTEM

Thermal transport in a full pressure suit, such as the Mark IV of the USN and the suit for Project Mercury, utilized a high flow rate of relatively dry, cool air passing between the suit and the occupant's body. In such a system, the occupant had to perspire profusely to accomplish the heat transfer from the body to the air.

A thermal transport system using circulating fluid in tubes in the undergarment was developed by Northrop, under contract, in 1962 (22). The requirement for the use of a fluid thermal transport system had been shown earlier by Belasco (23), but was not accomplished. At this time, however, the development of water conditioned suits was proceeding in England, the results being published in 1964 (24). Additional studies on the use of thermal transport by circulating fluid are currently being conducted by and for NASA/MSC for use in the extravehicular protective garments for projects such as Gemini and Apollo. More investigation is needed to determine the best manner in which to use this means of thermal transport since the thermoregulatory mechanisms of the body may alter blood flow unpredicably.

2.0 ANALYSIS

Investigation revealed that utilization of limit-stretch fluid-filled bladders would provide the dual requirement for the Internal Restraint System of thermal transport and acceleration protection. A discussion of the coolant system and the restraint system requirements is presented in the following paragraphs.

2.1 COOLANT SYSTEM

2.1.1 Physiological Aspect

Man is homeothermic, in that he is capable of maintaining a relatively constant temperature inspite of wide variations in surrounding environmental temperatures. Man's normal or "core" temperature refers to the temperature of tissues lying deep within the abdomen, thorax and head, It is generally measured orally or rectally. The core temperature varies from that of the superficial tissues such as the skin and muscles of the limbs. Core temperature of man at rest is 97° to 99.5° F (36° to 37.5° C) (25). The temperature range in which man can work efficiently is approximately 96.8° to 103.1° F (36° to 39.5° C) (26). To remain within these limits, a balance is maintained between the heat production and heat loss mechanisms of the body. Heat production results from metabolic activities, exercise, disease and environmental temperature. Under resting conditions, heat production is 1.8 Btu per pound (one Kcal per Kg.) of body weight per hour (25). Heat is lost by radiation, conduction, convection and evaporation. The skin plays a major role in maintaining this balance and acts as a heat exchanger between the deep tissues of the body and the external environment. The most effective system for thermal transport uses a conductive pathway to carry heat from the body.

2.1.2 Thermal Requirements

The thermal system (see Figure 1) is based on a continuous flow of water through the internal restraint bladders, during both the loaded and unloaded conditions. In the unloaded position, the gas ventilation system controls the insensible perspiration and is capable of removing 300 Btu/hr of heat.

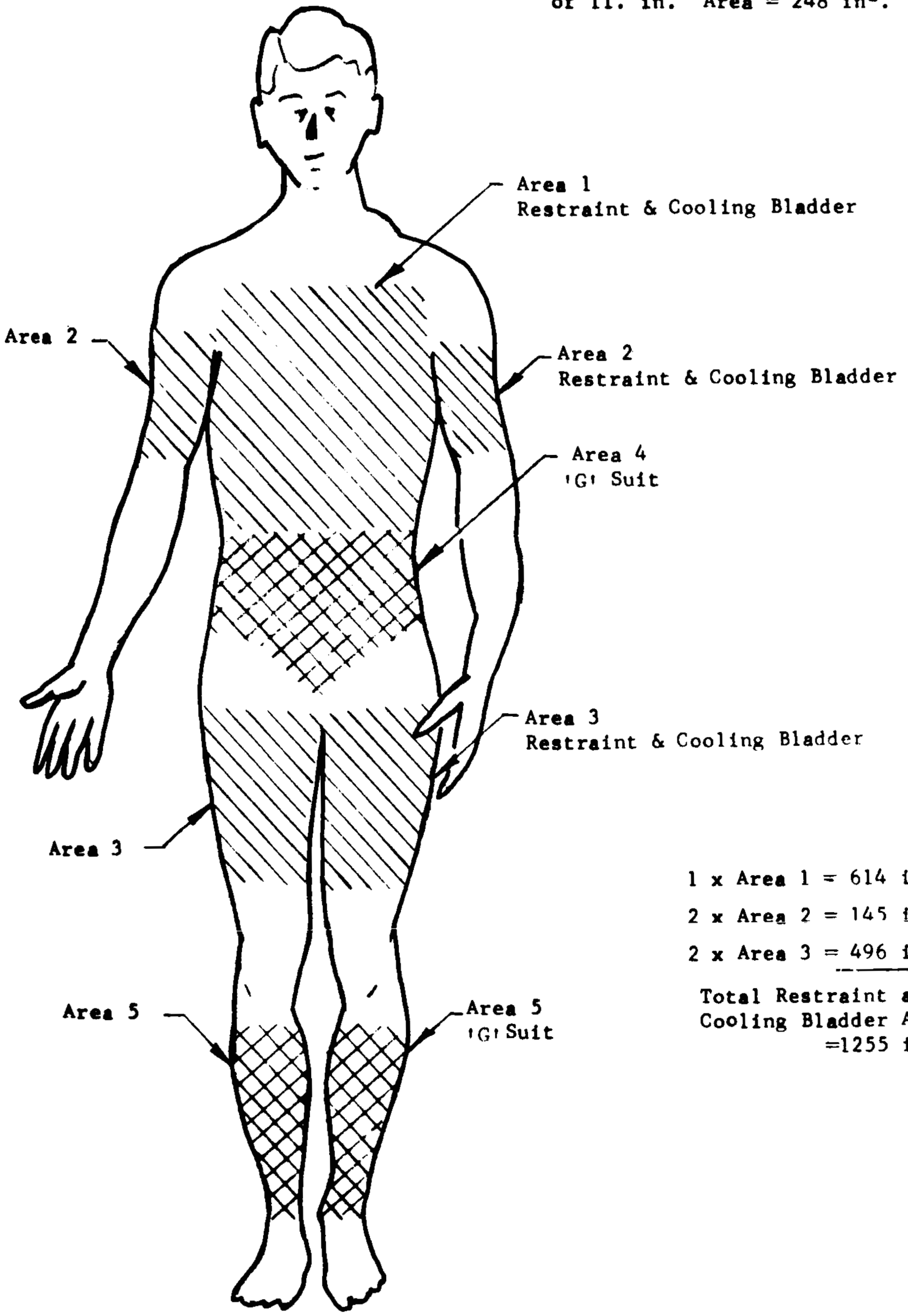
RESTRAINT BLADDER AREA

Areas approximated from the following measurements:

Area 1 - (Upper torso) chest 43.2 in; waist 31.7 in.; calculation based on a frustum of a right cone between shoulders and waist. Area = 614 in^2.

Area 2 - (Upper arm) 12.5 in. circ. x 5 in. long. Calculations based on a right cylinder. Area = 72.5 in^2.

Area 3 - (Thighs) Upper circ. of 25.3 in. Lower circ. of 19.6 in. and a length of 11. in. Area = 248 in^2.



1 x Area 1 = 614 in^2

2 x Area 2 = 145 in^2

2 x Area 3 = 496 in^2

Total Restraint and Cooling Bladder Area =1255 in^2

FIGURE 1 RESTRAINT BLADDER AREA

Thermal system maximum capacity = 2500 Btu/hr

The system change of temperature (T) of 5° F was decided upon to provide the optimum physiological comfort.

$$\text{System flow} = \frac{\text{Btu/hr}}{T} = \frac{2500\ \text{Btu/hr}}{5^\circ\ \text{F}} = 500\ \text{lb/hr}$$

With water density at 8.3 lbs/gal

$$\text{System flow} = \frac{500}{8.3} = 60\ \text{gal/hr or } 1\ \text{gal/min}$$

Assuming a minimum skin temperature of 75° F, and maximum water temperature of 40° F, the thermal conductivity (K) of 1/8 inch of material between the skin and water would be as follows:

$$K = \frac{q\ d}{A(T_1 - T_2)}$$

$$K = \frac{2{,}500\ \text{Btu/hr} \times .0104\ \text{ft}}{8.68\ \text{ft}^2 (75^\circ\ \text{F} - 40^\circ\ \text{F})}$$

$$K = .086\ \frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}}$$

where q = 2500 Btu/hr

d = 1/8 in. (.0104 ft)

A = 1250 inches ^{2} (8.68 ft^2)

T_1 = 75° F (Skin temp.)

T_2 = 40° F (Water temp.)

2.2 RESTRAINT SYSTEM

The restraint system is a load attenuation system designed to restrain and protect the wearer during long duration accelerations and to provide a high degree of protection during impact acceleration.

2.2.1 Physiological Aspect

By requirements, the force fields that the wearer may be exposed to are $\pm 30\ G_x$, $\pm 15\ G_y$, $+20\ G_z$, and $-10\ G_z$. To tolerate these loads requires containment of the wearer in a manner which will restrain the maximum mass and spread the imposed loads over a maximum area, preventing distortion of the body.

The use of water as a support medium, as in full fluid immersion presents the danger of surrounding the body with an incompressible fluid, which depending upon the pressure-volume relationship could crush the chest of the occupant during high $-G_z$ loads. The method of using a system of limit-stretch bladders between the man and the external pressure suit prevents this by giving support to the body by Archimedes principle without the fluid contact (Figure 2). Since the system must fit different sized people, some method of adjustment must be utilized. Within design limits the sizing can be accomplished by alteration of the degree of filling of the bladder system.

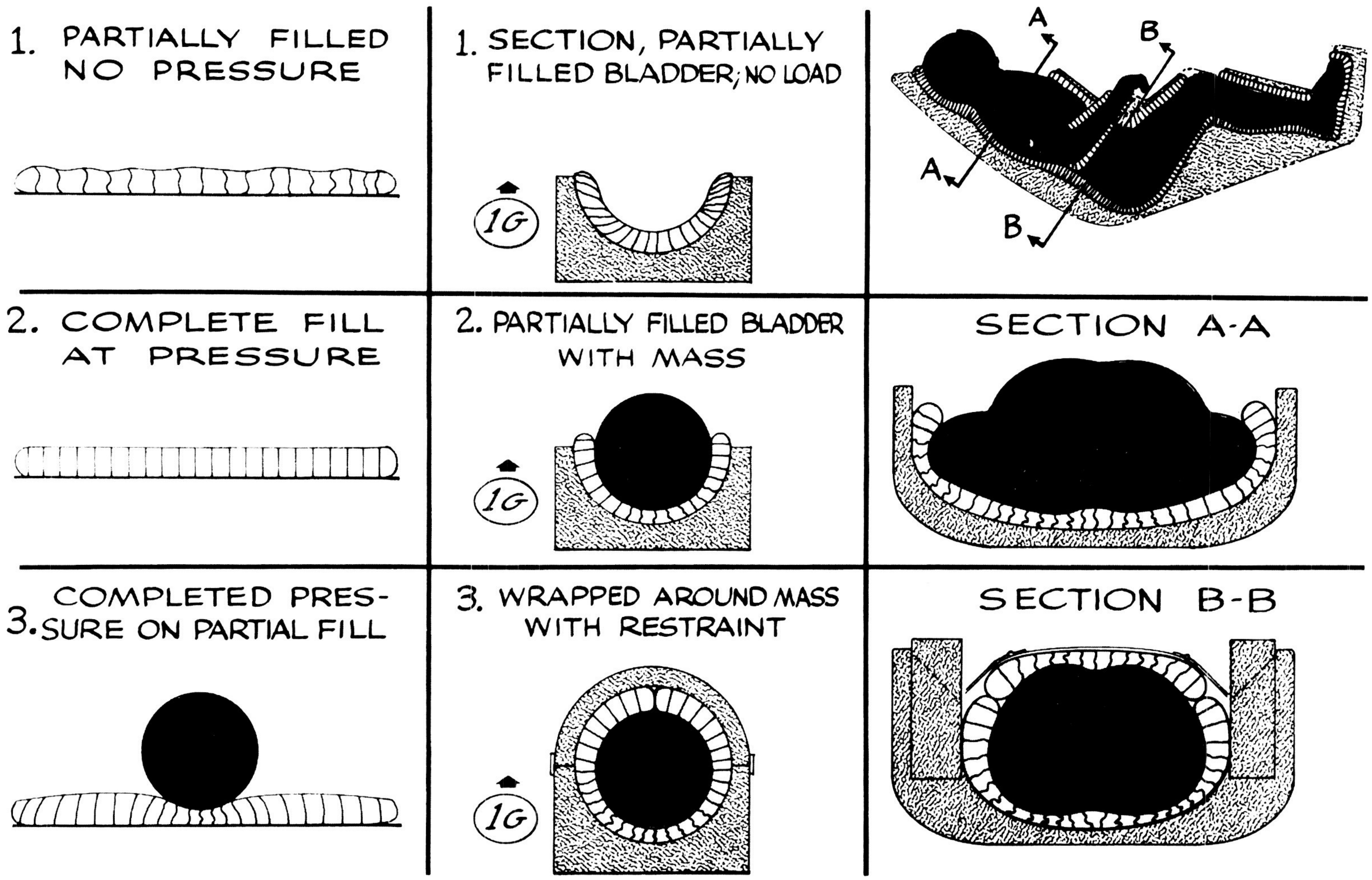


Figure 2 PRINCIPLES OF HYDRAULIC SUPPORT (BY LIMIT STRETCH WATER-FILLED BLADDER)

2.2.2 Load Requirements

Acceleration Fields: $\pm 30\ G_x$, $+20\ G_z$, $-10\ G_z$, $\pm 15\ G_y$

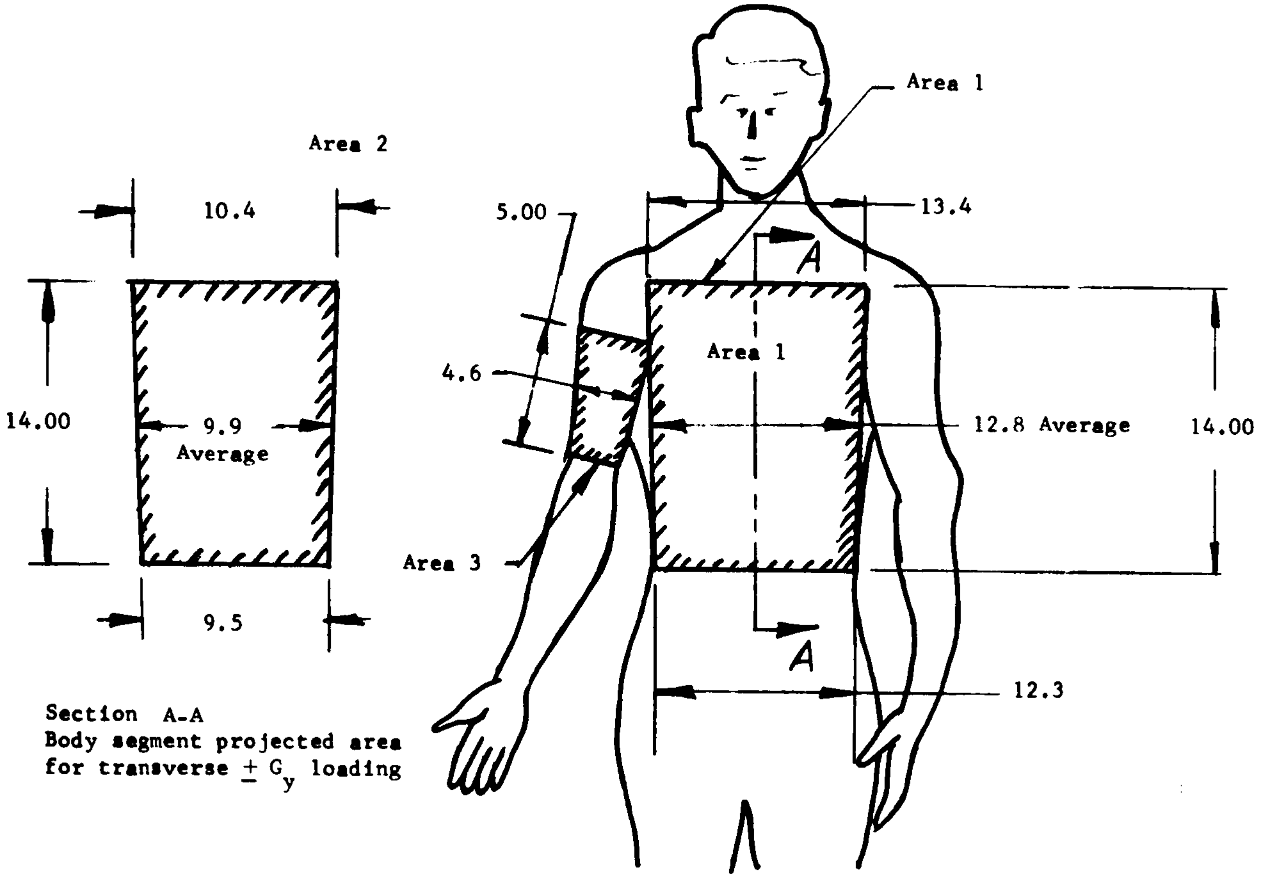
Body Segment Weight Distribution:

Neck to waist	(18%)	36 pounds
Pelvic area	(28%)	56 pounds
Upper arm	(3.3%)	7 pounds
Thigh	(10.7%)	21 pounds
Lower leg	(4.8%)	10 pounds

The anticipated unit load requirements on the pressure suit are determined by multiplying the body segment weight times the acceleration and dividing by the body segment projected area (Figure 3). A safety factor of 2 is used to give the occupant maximum safety.

$$\text{Suit load intensity} = \frac{2\ W\ G}{A}$$

Segment	Acceleration	Direction	Suit Load Intensity
Neck to waist	30 g	$\pm G_x$	12 psi
Neck to waist	15 g	$\pm G_y$	8 psi
Upper arm	30 g	$\pm G_x$	18 psi
Thigh	10 g	$-G_z$	5 psi
Thigh	20 g	$\pm G_z$	11 psi



Section A-A
Body segment projected area for transverse $\pm G_y$ loading

Body segment projected areas for transverse $\pm G_x$ loading

Area 1 (Neck to waist) = 12.8 x 14.0 = 179 in^2

Area 2 (Neck to waist) = 9.9 x 14.00 = 138.6 in^2

Area 3 (Upper arm) = 4.6 x 5.0 = 23.0 in^2

Other projected areas used in this report are calculated by the same method as shown above.

FIGURE 3 LOAD REQUIREMENTS

3.0 DESIGN

3.1 GARMENT

The garment is a supporting fabric medium containing the coolant tubes and the restraint bladder system. It provides sufficient mechanical pressure to insure intimate contact between the coolant tubes and occupant without restricting mobility. The fabric is porous to permit free flow of gas and water vapor, yet it possesses adequate strength to limit expansion of the contained restraint bladders. As shown in Figure 4 and 5, the bladders are contained in sleeves which are formed by attaching a second layer of fabric to the outer surface of the garment. Coolant tubes are positioned and retained between manifolds by loops of dacron material at required intervals. The use of an undergarment is not intended, although thin nylon or silk may be used without significant interference with the transport of body heat.

3.1.1 Material

The supporting fabric medium is a one-way stretch fabric (spandex). (The basic constituents of the fabric are 28% polyurethane, 28% acetate, 24% polyester, and 20% nylon). The elasticity of the material provides the necessary mechanical force to hold the cooling tubes in contact with the body and also provides a degree of sizing adjustment. In relation to the body, material stretch is circumferential. The expansion characteristics readily accommodate changes in body cross-section caused by wearer's movement. The open mesh construction offers little restriction to the free passage of gas or water vapor.

3.1.2 Sizing

Sizing of the internal garment system was determined by the pertinent anthropomorphic dimensions of Messers E. G. Lyman and H. C. Vykukal of NASA/AMES Research Center. Measurements of these two subjects are given in Table 1. In addition, a partial mannequin of fiberglass reinforced plastic of Mr. Vykukal was made available.

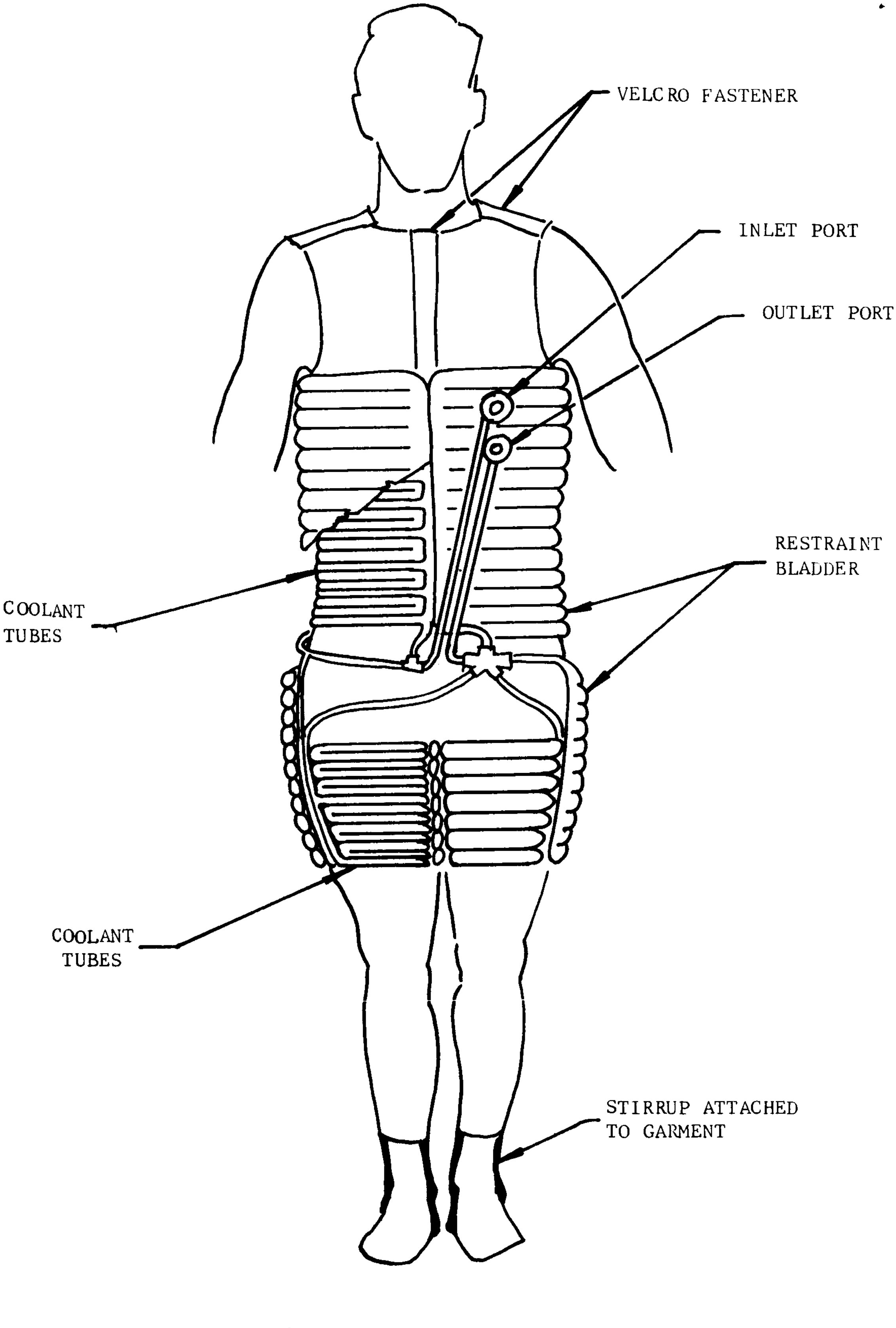


FIGURE 4 INTERNAL RESTRAINT CONFIGURATION

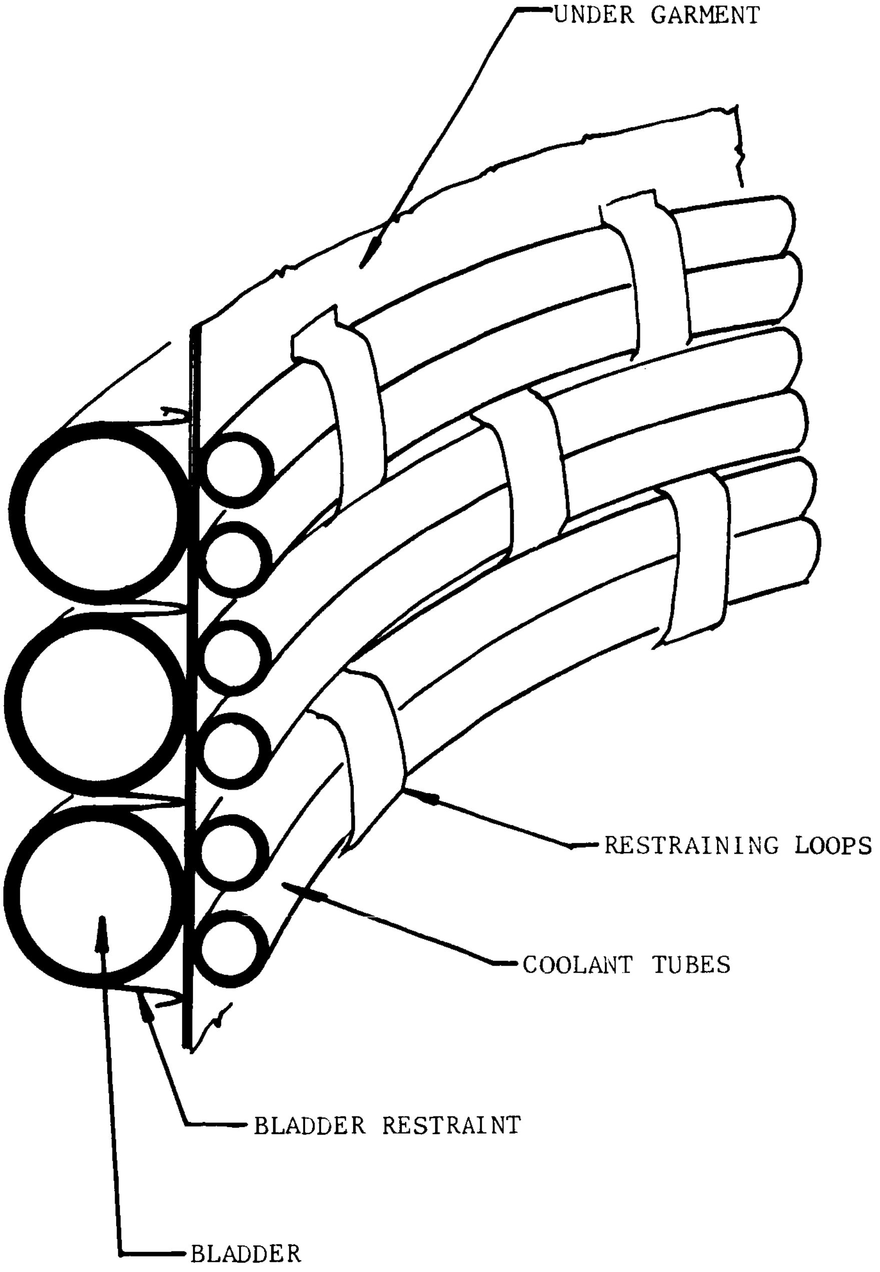


FIGURE 5 CROSS-SECTION OF COOLING TUBES & RESTRAINT BLADDER

TABLE I
ANTHROPOMETRIC MEASUREMENTS
OF
G. LYMAN AND H. VYKUKAL
NASA AMES RESEARCH CENTER

NOMENCLATURE		SUBJECT		Differences Inches
		Vykukal Inches	Lyman Inches	
A	Height	71 3/4	70 1/4	1 1/2
B	Weight	159	179	20
6	Cervical Height	60 3/8	60	3/8
7	Vertical Trunk Circum.	65 1/2	68 1/2	3
8	Acromial Height	59	57 1/2	1 1/2
9	Shoulder Circum.	44 1/2	45 1/2	1
10	Height Shoulder Circum. Level	56 1/2	54 3/4	1 3/4
11	Shoulder Breadth (Bideltoid)	18 3/8	19 1/4	7/8
12	Shoulder Length	6	5 1/2	1/2
13	Biacromial Dia.	12 1/4	12 3/4	1/2
14	Inner Scye	16	16 1/2	1/2
15	Nipple (thelial) Height	53	51 1/4	1 3/4
16	Chest Circum.	38	40	2
17	Chest Breadth	14	15 1/2	1 1/2
18	Chest Depth	9	9 3/4	3/4
19	Substernal Height	51	49	2
20	Suprasternal Height	58 3/8	57	1 3/8
21	Waist Height	43 1/4	42	1 1/4
22	Waist Circum.	31 1/2	35	3 1/2
23	Waist Breadth	11 1/4	12 1/2	1 1/4
24	Waist Depth	8 1/4	8 1/2	1/4
25	Waist Back	19	18 3/4	1/4
26	Waist Front	16	16	
28	Buttock Circum.	37	40 1/2	3 1/2
29	Height of Hip Circum.	37	35 1/2	1 1/2
30	Hip Breadth	13 1/4	14	3/4
31	Buttock Debth	8	9 1/2	1 1/2
32	Gluteal Furrow Ht.	32 3/4	31	1 3/4
33	Gluteal Arc	10 1/2		
34	Crotch Length	25	27	2
36	Upper Thigh Circum.	21	23 1/2	2 1/2
37	Ht. of Lwr. Thigh Circum.	23	22	1
38	Lower Thigh Circum.	15 1/4	15 1/2	1/4
47	Scye Circum.	18 1/2	19 3/4	1 1/4

Numbers in left hand column refer to designations in AMRL-TDR-63-55.

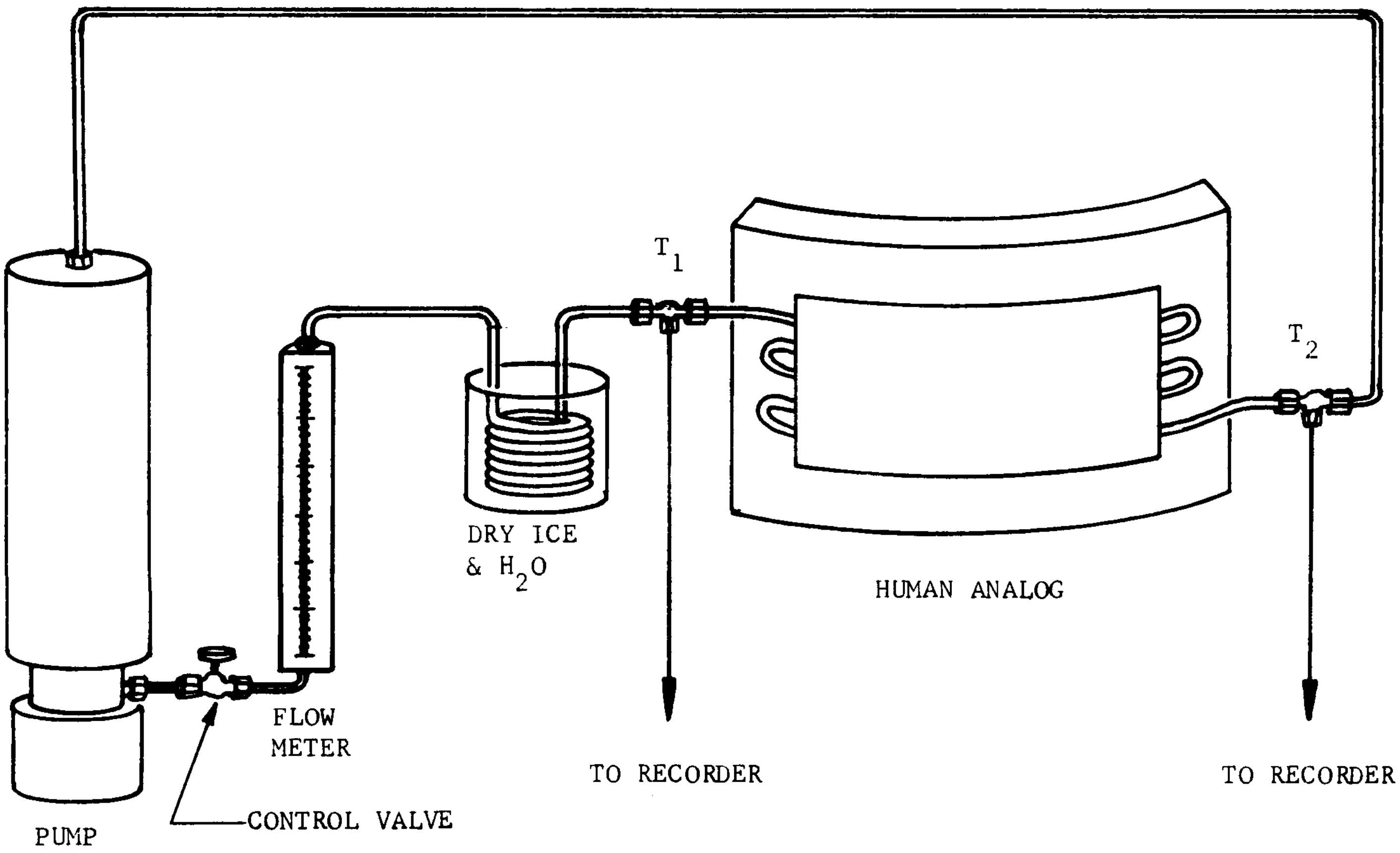


FIGURE 6 BREADBOARD TEST SETUP PICTORIAL DIAGRAM

Sizing was accomplished in two stages. A prototype garment system was fabricated and measurements made with each of the subjects wearing it. These measurements then were used to correct the sizing for the final system.

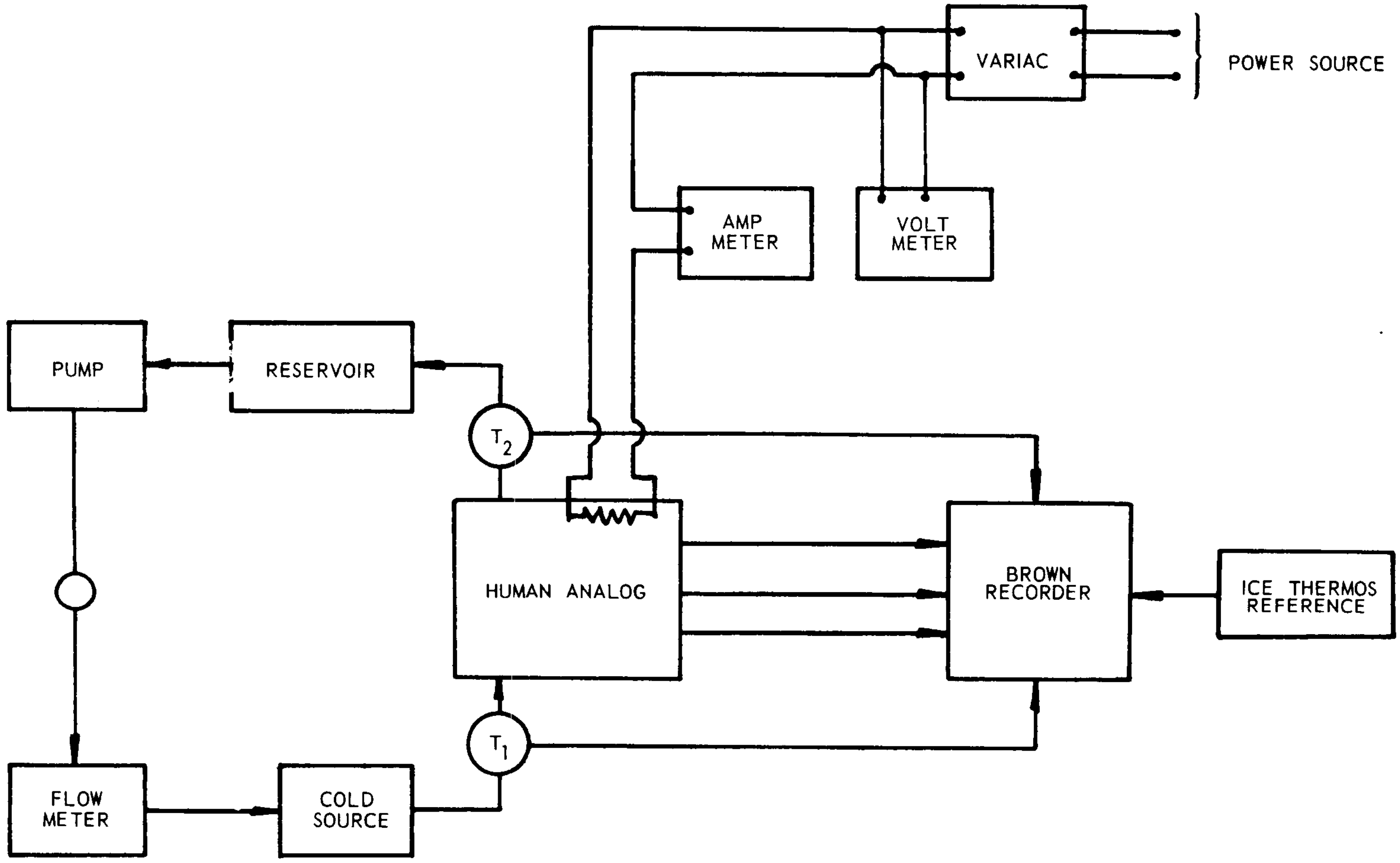
Significant differences between the two subjects exist in the chest and waist areas. Although the garment and closures provide a certain amount of sizing, additional adjustments are made available via a double velcro insert for the torso area to accommodate these differences.

3.2 COOLANT SYSTEM DEVELOPMENT

Initial studies of the cooling system were based on the concept of using the same bladders for both cooling and internal restraint. A series of test panels were made to test the concept and to determine fabrication methods.

3.2.1 Apparatus

The breadboard tests of the cooling system were conducted on the apparatus as shown on pictoral diagram Figure 6. The cooling water was circulated by a pump mounted on the bottom of a reservoir. Flow from the pump to the system was regulated by a valve and monitored by a flowmeter. The test panels were mounted on a two foot square test fixture that was designed to simulate a portion of human body for thermal transport experiments. The test fixture consisted of a tanned, horsehide cover over a 1/8 inch thick convex copper plate serving as a heat distributor. The concave side of the copper plate was covered with a potted heating element (two layers of epoxy bonded glass fabric containing the heating elements). A half-inch thick pad of insulation covered the potted heating elements and was held in place by a thin sheet of aluminum. Eight thermocouples were placed on the test fixture to sense the temperature of the simulated skin. Temperatures of the coolant into and out of the test panel were sensed by thermocouples mounted in the coolant lines adjacent to the test fixture. All thermocouple readings were recorded on a Brown recorder. Temperature of the test panel was regulated by a variac and monitored by a voltmeter and an ammeter as shown in Figure 7.



T_1, T_2 = THERMOCOUPLE PICKUP

FIGURE 7 SCHEMATIC OF TEST SET UP

3.2.2 Test Results (Coolant System)

Test Panel No. 1 - The first test panel made was based on a design which used a no-stretch material and allowed the expansion required for internal restraint to be accomplished by the unfolding of the material as shown in Figure 8.

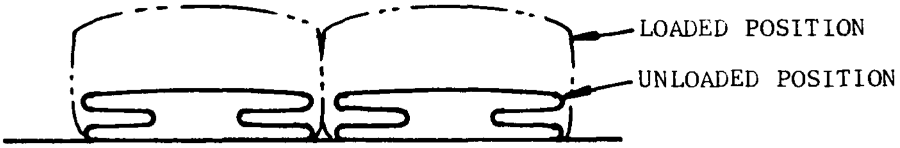


FIGURE 8 TEST PANEL NO. 1 CROSS SECTION

The tubes were fabricated by wrapping a cotton fabric coated on one side with unvulcanized neoprene over a mandrel and curing in an oven. Tests indicated that with a no-stretch material, new and expensive processes of fabrication would need to be developed to form the bladders around the body. High tooling cost resulted in the rejection of this design.

Test Panel No. 2

This test panel was based on the same concept as test panel #1 except the bladder was made of a limit-stretch material. The bladder material used was spandex coated with vinyl. The bladders were fabricated by wrapping spandex around a mandrel and dip coating with "liquid" vinyl. Pressure tests indicated the design would give the desired results for the restraint bladders; however, small pin hole leaks were virtually impossible to eliminate. Therefore, the design was rejected.

Test Panel No. 3

To keep the design as simple as possible, the third design concept was based on the use of a rubber tube restrained by a limit-stretch fabric as shown in Figure 9.

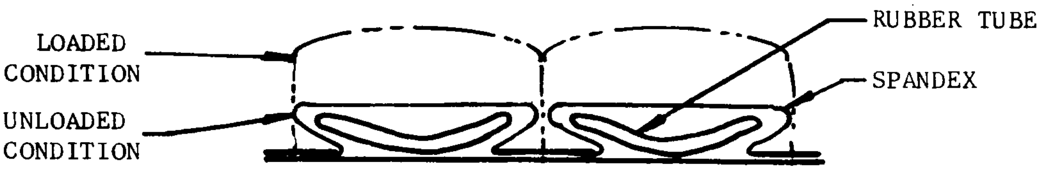


FIGURE 9 TEST PANEL NO. 3 CROSS SECTION

A 24 inch long test panel was fabricated using spandex as the limit-stretch material and rubber gooch tubing as the bladder material. Results of the bladder segment were as follows:

Area of test segment 24 in^2

Flow rate = 0.36 lb/min

Inlet temperature = 45° F

Outlet temperature = 52° F

$\Delta T = 7^{\circ}$ F

Skin temperature = 88° F

Q (for 24 in^2) = $0.36 \text{ lb} \times \frac{60}{1 \text{ hr}} \times 7^{\circ} = 151.2$ Btu/hr

Q (for system) = 22 x 151.2 = 3,322 Btu/hr

The design had the advantages of having a large contact area with the body and was capable of providing adequate cooling. The disadvantages were the large amount of fluid in the system, and the difficulty of manifolding the flow to prevent non-uniform heat exchange.

Test Panel No. 4

Because of the large volume of water required in the single bladder designs, a decision was made to split the system into two segments, one portion to be used for cooling and the other portion to be used when restraint was required. The restraint portion consisted of a rubber tubing incased in a limit-stretch fabric. The cooling portion was tygon tubing incased in spandex fabric (Figure 10).

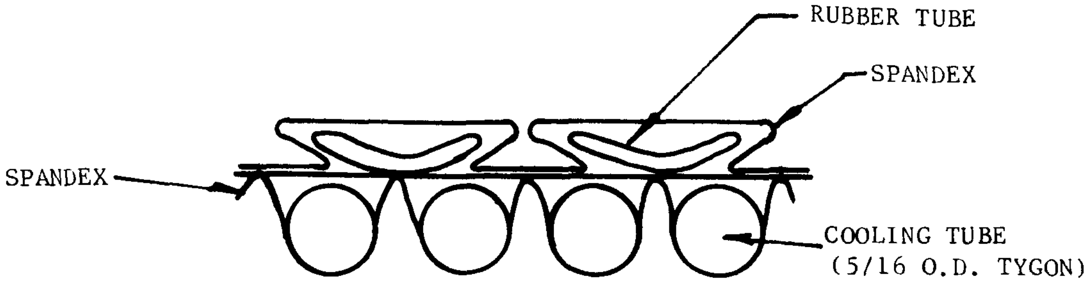


FIGURE 10 TEST PANEL NO. 4 CROSS SECTION

The results of a test on 50 in^2 (1/16 of the proposed system) were as follows:

Area of test segment 50 in^2

Flow = 0.57 lb/min

Inlet temperature = 40° F

Outlet temperature = 43° F

$\Delta T = 3^{\circ}$ F

Q (for 1/16 of system) = 3° F x 0.57 lb x $\frac{60}{hr}$ = 102.6 Btu/hr

Q for system = 102.6 x 16 = 1642 Btu/hr

The system as tested was 1000 Btu/hr short of the design requirements. In all other respects the dual system seemed adequate.

Test Panel No. 5

A test panel was fabricated using the same design concepts as used in test Panel No. 4 except the material used to cover the cooling tubes was changed to nylon fabric covered with Buna-N.

Test area = 50 in^2

Flow = 0.57 lb/min

Inlet temperature = 35° F

Outlet temperature = 40° F

$\Delta T = 5^{\circ}$ F

Q (for 1/16 system) = 5 x 0.57 x 60 = 171 Btu/hr

Q (for system) = 171 x 16 = 2763 Btu/hr

The test indicated that 2500 Btu/hr could be taken out of a 800 in^2 area if the thermal conductivity could be increased.

Test Panel No. 6

A panel was fabricated using neoprene tubing covered with spandex (Figure 11).

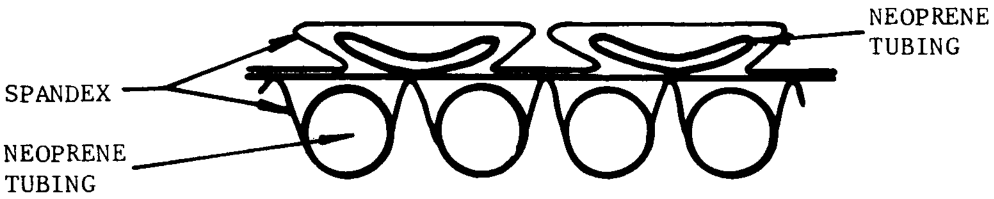


FIGURE 11 TEST PANEL NO. 6 CROSS SECTION

The tubing was made 100 in. long to simulate 1/16 of the total system. The panel was mounted on the human analog and tests were run as follows:

Flow rate = 0.57 lb/min

Btu (in) = $\frac{\text{watts}}{0.2931}$ - Btu loss

Btu (loss) = 34 Btu with analog at 90° F

Btu (out) = 0.57 lb x $\frac{60}{\text{hr}}$ x ΔT = 34.2 x ΔT

System Btu = Btu (out x 16)

Run	Btu(in)	Tin	Tout	ΔT	Btu(out)	System Btu	Skin temp.
1	176	35.5	40.5	5	171	2736	90
2	176	35.5	41	5.5	188	3010	90
3	176	36	41	5	171	2736	90
4	145	36	40.5	4.5	154	2465	90
5	140	37.5	41.5	4.0	137	2195	90
6	138	37	41.5	4.5	154	2465	90
7	138	49	52.5	3.5	120	1920	93°
8	65	67.5	69.5	2.0	68.4	1095	90°

Tests indicated that the configuration used in Test Panel No.6 satisfactorily met requirements previously established. Discrepancies in Btu output (run No. 1 and 2) from what appears be be equal input are due to reading error, temperature recording system accuracy, ammeter and voltmeter accuracy and line voltage variations.

3.2.3 Material Coolant Compatibility

In the liquid containing portion of the integrated restraint-pressure suit, distilled water coolant if used as recommended will be in direct contact with the aluminum suit fittings and with the neoprene rubber tube circulation system. If the system is to operate at 35° F continuously, an anti-freeze mixture of water with 10% ethylene glycol by volume should be utilized as the coolant to preclude ice formation in the heat exchanger. However, the strong unlikelihood of prolonged system operation at temperatures as low as 35° F has prompted the selection of distilled water alone for use as the coolant. The other materials, 6061 type aluminum used for the suit fittings and neoprene rubber used for the circulation system tubing, were selected not only for their mutual compatibility from the standpoint of dissimilar materials and corrosion, but also for their ease of fabrication.

Neoprene has been chosen as the material for the cooling system tubes because (1) it is the most compatible with the suit environment of 100% oxygen, (2) it is resistant to body contaminates, (3) its resistance to the adverse effects of water is rated as excellent when compared to other rubbers under similar environmental conditions (Reference 27), and (4) satisfies the need for a material with as high as possible thermal conductivity for maximum heat transfer.

In light of the foregoing, the subject materials should perform exceptionally well in the intended application.

3.3 RESTRAINT SYSTEM

Materials for the restraint system are the same as used in the coolant system.

4.0 WORKING LABORATORY MODEL

Based on the positive test results obtained, a full-size working laboratory model of the Internal Restraint System was fabricated. A schematic diagram of the entire system is shown in Figure 12.

4.1 EXTERNAL CONFIGURATION

The external configuration of the Internal Restraint System is shown in Figure 13, 14 and 15. The garment is made of spandex and resembles a sleeveless union suit*. Stirrups prevent the garment legs from vertical displacement. Spandex sleeves containing restraint bladders are located around the trunk and thighs.

4.1.1 Closures

All garment closures are effected with nylon fasteners (velcro). Two main advantages offered by the usage of velcro are (1) it affords an adjustable closure and (2) it is non-metallic.

The primary garment closure is located on the front center of the garment and runs from the neckline to the waist. Secondary closures are located on the top of each shoulder and on the outer side of each leg. These closures allow an added degree of adjustment.

4.2 COOLANT SYSTEM DESIGN

The following design is based on results obtained from the system development tests.

Contract requirements stipulate that not more than 50% of the body area shall be utilized for cooling purposes. The area covered by the cooling system is the same area covered by the restraint system except in the buttocks. The areas selected contain the greatest mass and also produce most of the metabolic heat.

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*Subject wearing t-shirt under garment

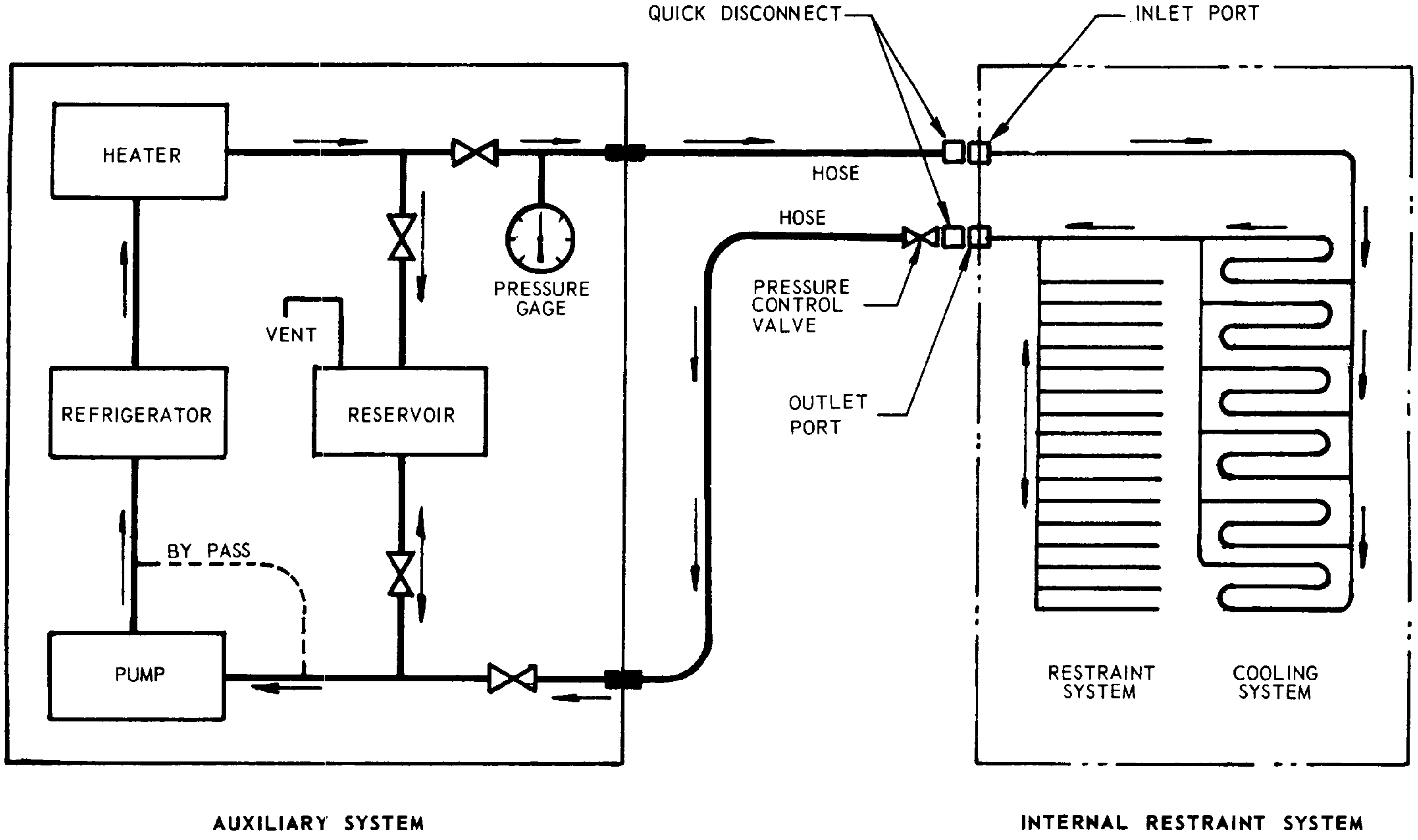

FIGURE 12 SYSTEM SCHEMATIC DIAGRAM

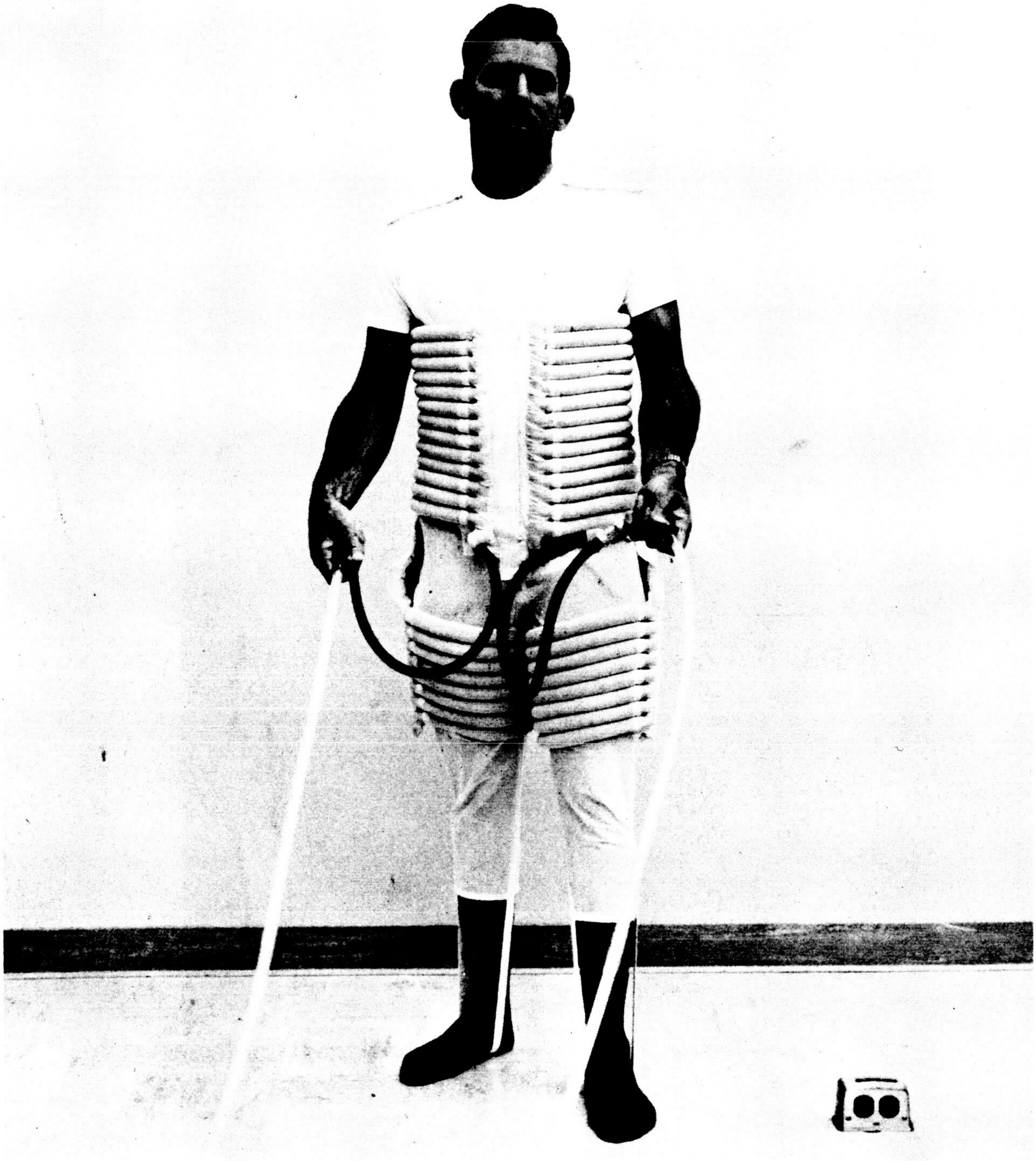

FIGURE 13 INTERNAL RESTRAINT SYSTEM (FRONT VIEW)

FIGURE 14 INTERNAL RESTRAINT SYSTEM (SIDE VIEW)

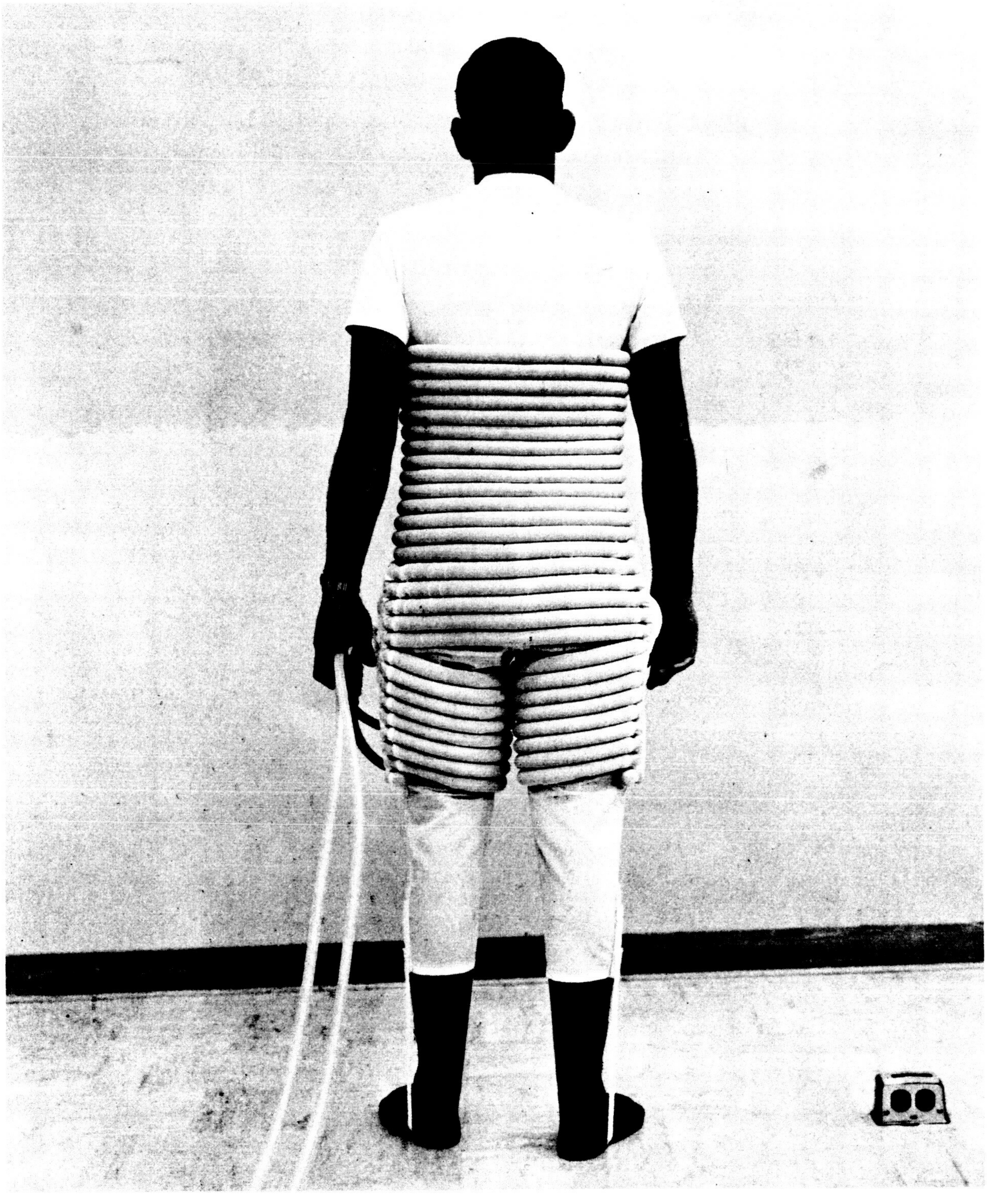

FIGURE 15 INTERNAL RESTRAINT SYSTEM (REAR VIEW)

The cooling system consists of a series of parallel tubes encompassing the body area from the nipples to the hips, and both thighs (Figure 4 and 5). Coolant tubes are extruded neoprene rubber, round in cross section with a 1/4 inch inside diameter and a 1/32 inch wall thickness. The tubes are attached to the garment by dacron loops spaced at appropriate intervals. The total area of coverage for Messrs Lyman and Vykukal is 0.56 and 0.50 square meters respectively, which is approximately 25% of the total body area.

Coolant flow is one gallon per minute. The total coolant system capacity is approximately 0.35 gallons (3.00 pounds). Coolant medium is water. Although the system was designed for water or water-glycol, tests indicate that a 2500 Btu metabolic heat removal can probably be attained without the glycol additive.

4.3 RESTRAINT SYSTEM DESIGN

The restraint system is a series of parallel bladders encompassing the body in the same areas as the cooling system tubes (Figure 4 and 5) with additional bladders being provided in the buttock areas. Bladders are extruded neoprene rubber, round in cross section, with an inside diameter of 7/8 of an inch and a 1/32 inch wall thickness. Expansion of the bladders is limited by encasement in one-way stretch material. The restraint bladders have no through flow. Bladder volume and pressure is controlled by restricting the return flow from the suit to the pump, thus forcing water into the restraint bladders. A valve at the suit water exit port is used to control the system volume and pressure. Experimentation may indicate the need for controls to permit separate volume adjustment.

Lacing on the external restraint system will be utilized to provide for proper fitting between the pressure suit and the internal restraint system.

4.4 MANIFOLDS

Manifolds for coolant and restraint systems are fabricated by a neoprene dipping process utilizing aluminum mandrels for the desired configuration. Coolant tubes and restraint bladders are bonded to the manifolds by means of a two part self-curving neoprene adhesive (UBS Chemical Co N-136 Ubagrip). Manifolds are encased in a lightweight dacron material and sewn into position on the garment. They are located down the front center of the garment and down the outer portion of each leg, and are interconnected.

In addition, two distribution chambers, which may also be termed manifolds, are fabricated from aluminum alloy and provide entrance and exit ports for the restraint and cooling system manifolds.

4.5 INLET AND OUTLET PORTS

Inlet and outlet ports are located in the left chest area to conform to the pressure suit configuration. The inlet and outlet ports incorporate a quick disconnect valve design which is used in conjunction with a Snap-tite self-sealing coupling. Disconnecting these couplings will not cause pressure loss or water leakage. The fittings, for adaptation of valve to pressure suit ports and valve, are fabricated from aluminum alloy and finished with a hard anodic coating (Figure 16).

Flexible interconnecting lines extend from the ports to their respective distribution chambers.

4.6 CONTROL VALVE

The control valve is fabricated from aluminum alloy and so constructed to allow free flow in one direction and adjustable restricted flow in the opposite direction.

This valve is located in tandem with the quick disconnect coupling on the suit outlet line, between it and the auxiliary system. This location will be convenient for the suit wearer to regulate the outlet water flow for purposes of loading or unloading the internal restraint bladders.

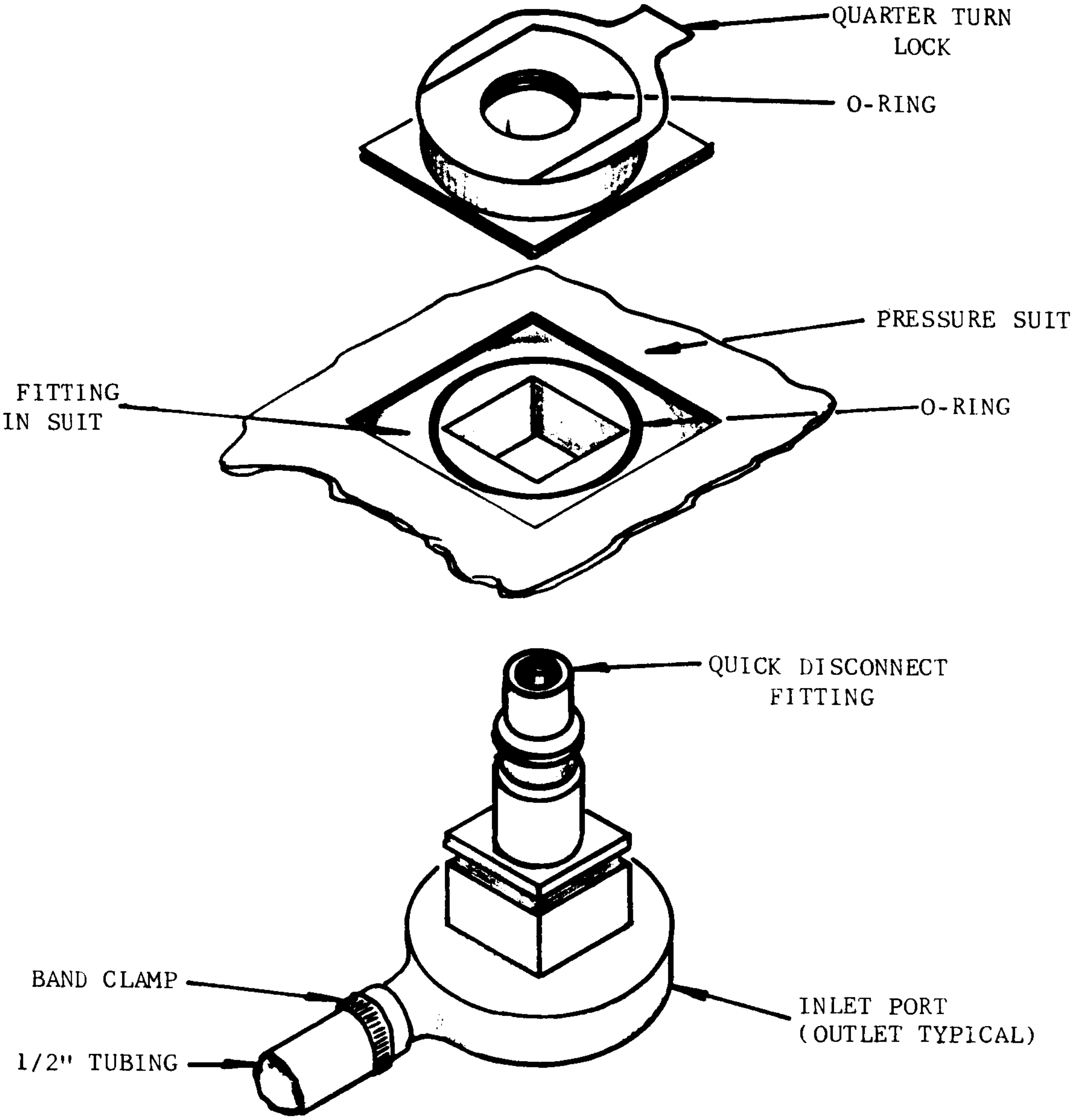

FIGURE 16 SUIT FEED THROUGH FITTING

5.0 AUXILIARY SYSTEM

The auxiliary system is essentially a fluid pump and heat exchanger and is shown in Figure 17. Figure 10 shows a schematic diagram of the system. Its functional characteristics are dictated by the necessary physiological requirements for proper operation of the Internal Restraint System. The pump portion of the system will provide a constant one gallon per minute flow of water over a pressure range of 5 to 25 psi gage, and the heat exchanger is capable of handling 3000 Btu/hr with a 35° F outlet water temperature. Operational procedure for the auxiliary system is attached as appendix.

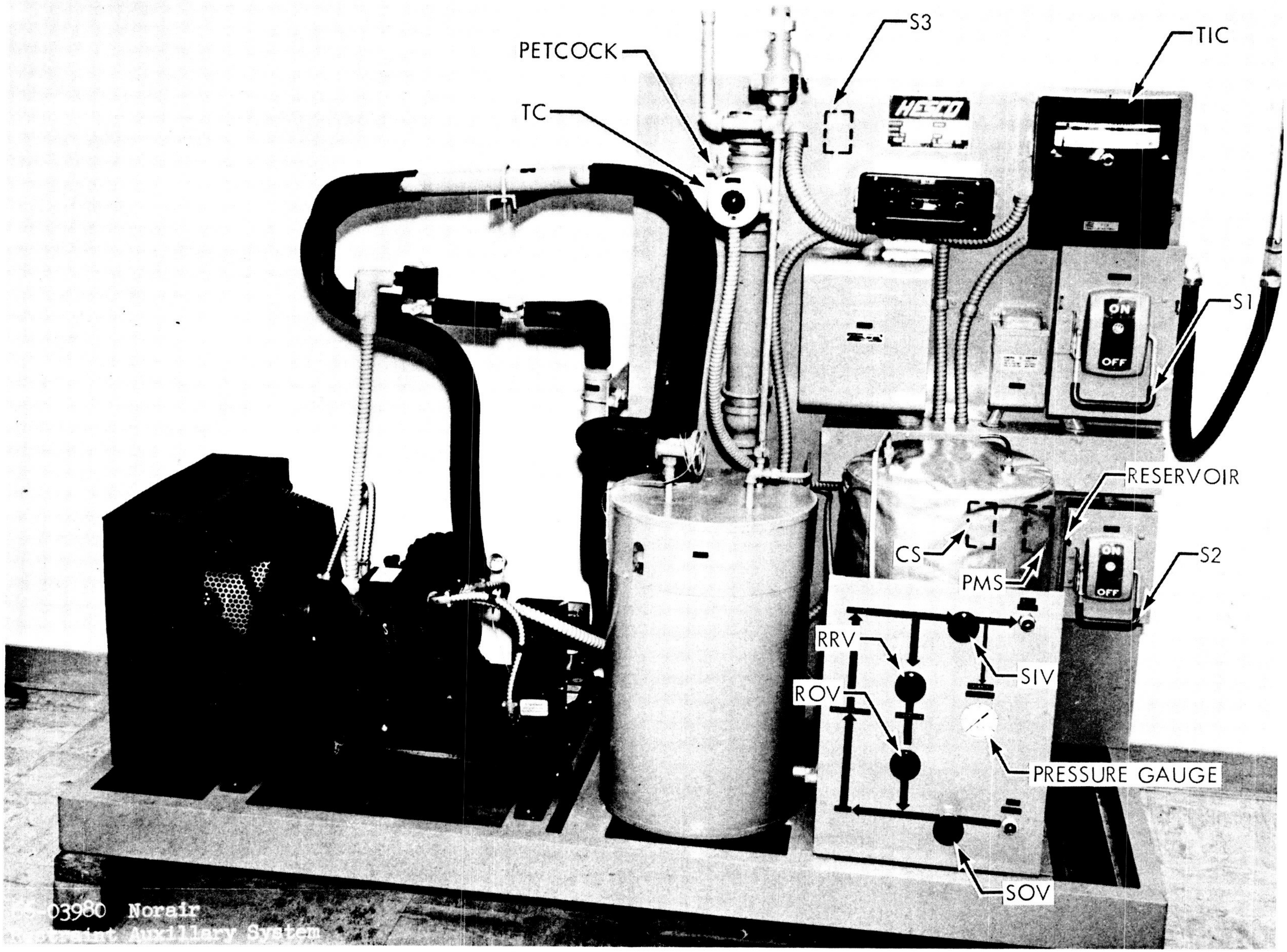

FIGURE 17 AUXILIARY SYSTEM

6.0 CONCLUSIONS AND RECOMMENDATIONS

A working laboratory model has been developed which results in considerable advancement in technology of support-restraint and thermal control of a man in a full pressure suit. The system provides a load transfer pathway between the man and the Integrated Pressure Suit System by means of liquid-filled bladders. Thermal control is accomplished by direct conduction of metabolic heat from the man to fluid-filled coolant tubes.

The effort to date on the development of this system has been confined to proving the feasibility and the fabrication of a laboratory model for substantiation of the concept. More work remains to be done if this concept is to become integrated into a fully accepted service item.

Further effort should at least include:

(1) Study to determine the possible need for a separate shut off valve for restraint bladder control.

(2) Study to determine the adequacy of the restraint system in terms of body area covered.

(3) Study to determine the feasibility of integration of an anti-g suit feature.

(4) Evaluation should be as to comfort, work level, effect of raising and lowering temperatures of cooling system, concomitantly or post exercise, and other variables to determine the effect on the physiological mechanisms controlling thermoregulation.

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APPENDIX

Auxiliary System Operation

General

The auxiliary system was designed to provide a closely controlled fluid coolant medium for the Internal Restraint System. It will operate within the following design limits:

1. Coolant temperature control from 35 to 80 degrees F with a tolerance of plus or minus 3/4 degree from set temperature.
2. Provide a one gallon per minute coolant flow over a pressure range of 5 to 25 psi.
3. Heat five gallons of coolant from 35 to 80 degrees F within a period of 10 minutes and cool a like amount from 80 to 35 degrees F within 20 minutes. (test results indicate these time periods were substantially reduced).

Distilled water, or an anti-freeze mixture of distilled water and 10% ethylene glycol by volume, should be used as the coolant medium. For continuous operation below 40° F the water-glycol mixture must be used. A six and one half gallon capacity reservoir contains the coolant supply and is an integral part of the auxiliary system. Four regulating valves and a pressure gage are mounted on a control panel and regulate both inlet and outlet coolant flow for suit and reservoir. A pictorial description of the Auxiliary System is shown in Figure 17.

Operation

1. System Fill

Fill the system with five gallons of appropriate coolant medium using the following procedure:

- (a) Close suit inlet valve (SIV) and reservoir return valve (RRV).
- (b) Open suit outlet valve (SOV) and RRV.
- (c) Set temperature indicator control (TIC) to 30° F and temperature controller (TC) to 100° F.
- (d) Switch S1, S2, and pump motor switch (PMS) to the on position.

Water can now be drawn into the reservoir utlizing pump suction. When filling is completed close the SOV and RRV. Open the reservoir outlet valve (ROV) and bleed all air from the system by means of the petcock located at the top of the heater unit. Connect suit inlet hose to the auxiliary system and open SIV. Using the male half of the quick disconnect coupling, expel air from hose. Close SIV and ROV. Connect suit outlet hose to auxiliary system and Internal Restraint System. Open SOV and RRV. Allow system to operate in this condition until the internal restraint garment is evacuated of air. Close RRV and SOV. Open ROV and again bleed the system of air at heater petcock. Connect suit inlet hose to internal restraint garment and open SIV and SOV. Allow coolant to circulate for a period of five to ten minutes, bleeding air from system periodically. The system is now ready to provide temperature and pressure coolant control for the Internal Restraint System.

2. System Control

S1 and S2 are main power switches and remain in the on position until a complete shutdown of the system is desired. S3 is a heater element control switch with position designations of high and low. High position demands full 9KW power of the heater and low position utilizes 2/3 of this power. Full heater power is only necessary for a rapid increase in coolant temperature from 35 to 80 degrees within the previously specified time limit. Nornal system operation will utilize the low position.

The TC is a thermoswitch for controlling the condenser unit. It will activate the condenser unit on a coolant temperature rise above the indicated dial setting and vice versa. The temperature sensing tolerance is between 3 and 5 degrees.

After system fill procede as follows:

(a) Dial TIC red pointer to desired temperature.

(b) Turn compressor starter (CS) on and dial TC to the appropriate setting. The TC setting should always be 5 degrees lower than the TIC.

(c) Black pointer on TIC is the actual suit inlet water temperature. It may be necessary to adjust the reset, located under the lower front cover of the TIC, to obtain correct cycling and maintain the set temperature within desired tolerance. Only small incremental adjustments are necessary when utilizing the reset.

The operator should be familiar with the instruction and installation manuals on the component parts of the Auxiliary System.

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