AMRL-TR-66-143

AD647197

RESEARCH AND DEVELOPMENT OF EXTRAVEHICULAR PROTECTIVE ASSEMBLY

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OCTOBER 1966

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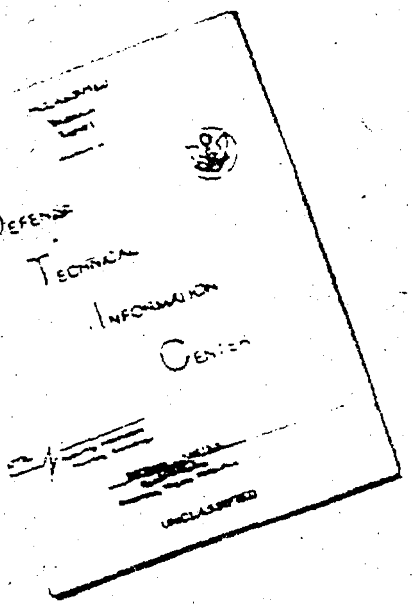

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FOREWORD

This study was initiated by the Biomedical Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The research was conducted by the David Clark Company, Incorporated, Worcester, Massachusetts, under Contract No. AF 33(657)-9532. The work was performed in support of Project 6301, "Aerospace System Personal Protection," Task 630104, "Space Protective Garments." Research sponsored by this contract was started 2 July 1962 and was completed 30 April 1964.

The data on the research accomplished were submitted by Norman H. Osborne of the David Clark Company, Incorporated. The data were assembled by Lee C. Rock, contract monitor for the Aerospace Medical Research Laboratories.

This technical report has been reviewed and is approved.

WAYNE H. McCANDLESS
Technical Director
Biomedical Laboratory
Aerospace Medical Research Laboratories

ABSTRACT

A prototype extravehicular pressure suit assembly was designed and fabricated for use in earth and lunar environments. Conditions of space environment, preliminary design concepts, laboratory evaluations of materials, the intermediate model configuration, and the final suit assembly are described in detail. This assembly consists of special underwear, liner, ventilation system, gas container, restraint layer and cover, insulation, micrometeorite protection, an outer reflective layer, and a life support system. The life support system is a liquid oxygen, semiclosed, recirculating-type backpack. The use of new material distinguishes this assembly from current pressure suits. Recommendations for further research and development are included.

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INTRODUCTION

Review and evaluation of the physiological and aeromedical aspects of space travel and the space environment revealed that significant improvements in existing protective pressure assemblies were required to provide adequate personal protection for the space explorer. In addition, an examination of the past history of pressure suits, their development and application and, in particular, the materials used indicated that, although the basic principles of pressure suit design could be used, extensive change of materials was needed to satisfy protection requirements.

The primary objectives of this project were to develop an extravehicular pressure suit assembly which would protect the human body from the hostile environment of space and would permit the wearer to obtain a high degree of mobility to perform body movement functions for predetermined tasks while in a pressurized state.

The completed assembly, without the environmental control system attached, must not weigh more than 25 lbs and must be capable of:

1. Operating at 5-psi differential pressure while maintaining a leak rate of less than 100 cc/min and 8 in. of water maximum back pressure at maximum vent flow.

2. Holding a pressure of 12 psig for a period of 30 minutes.

3. Fitting any subject in the medium regular size range of the Eight-Size Height-Weight Sizing Program.[1]

4. Being donned by a trained subject in less than 5 minutes.

In development of the assembly the following environmental space hazards had to be considered:

An extreme vacuum exists in space with pressure in the order of 10^{-14} mm Hg. In this vacuum heat transfer is exclusively by radiation. Although the solar constant at the top of the earth's atmosphere remains approximately 2 cal cm^{-2} min^{-1}, temperatures on the moon may reach +140 C (+284 F) at lunar noon and -150 C (-238 F) at lunar midnight. Furthermore, extremely large and rapid changes in thermal conditions may occur. In 1 hour, for example, temperatures ranging from +130 C (+266 F) to -117 C (-179 F) have been observed.[2]

Solar glare at the top of the earth's atmosphere is approximately 140,000 lumens/meter^2 of flux. Because there is no indirect sunlight in space, the sky is dark despite a brightly shining sun. Everything exposed to sunlight, inside and outside the cabin, appears extremely bright while everything in shadow appears quite dark. Contrasts of visual fields and retinal adaptation require special attention to lens optics. Retinal damage can result if the space traveler looks directly into the sun.

Meteoroid velocity is estimated to be about 42 km/sec at the earth's orbital distance. Because of the earth's orbital velocity, 30 km/sec, impact velocity on the moon and earth is approximately 60 km/sec. A mass of 1 mg traveling at 40 km/sec is capable of penetrating 3 mm of aluminium.[2,3,4] Thus, even impingement of meteoritic dust and particles causes an erosion or sandblasting effect on the external covering or coating, and large particles of cosmic dust (porous balls which shatter easily) result in spalling of the contact surface.

The original suit design, based on results of past research and present protection requirements for exposure to a space environment, was altered during investigation to accommodate newly developed and satisfactorily evaluated materials. Further modifications were also made when preferred materials were not immediately available in sufficient quantities or were not sufficiently developed to be used in this assembly.

The materials finally selected for this program appeared to withstand the rigors of vacuum, rapid and extreme temperature changes, X-ray type radiation, and the impact of high velocity projectiles both in the laboratory and in operational use under simulated space conditions.

The final configuration, which is described in detail beginning with the original assembly designs and concepts and continuing through the intermediate model, basically resembles the current full pressure suit, i.e., gas container, ventilation system, restraint layer, and exterior reflective cover. Additional components have, however, been added for insulation and micrometeorite protection; materials used in conventional full pressure garments have been replaced with HT-1 fabric, line thread, restraint, Omni® coating, stainless steel, ballistic felt, aluminized Mylar® and Leno® ; and a life support backpack featuring a liquid oxygen semiclosed recirculating system has been added.

SECTION II

PRIMARY APPROACH

A. Basis of Material Selection

Strength and high temperature compatibility, low temperature flexibility, effects of and protection against radiation, outgassing of the material in high vacuum, and toxic elements potentially present in the internal environment of the assembly were specific points considered in making the material selections. Consideration was also given to noise, vibration, impact, abrasion, temperature and external dynamic pressures, water absorption, creeping, thermal protection, mobility, comfort, ventilation, and metabolic output. Structual materials believed to be compatible with space and vehicle environments were selected for all components.

Unlubricated metal against metal has a tendency to seize in the space environment. Lubricants, such as molybdenum disulfide, silver and gold films, appear to be compatible with the space environment. Low vapor pressure greases would also be satisfactory providing they are compatible with oxygen under pressure. Nonporous stable coatings provide excellent protection of the material at temperatures below -65 C (-85 F) to above +204 C (+400 F) while in a vacuum.

Among the many conditions attributed to space radiation is ionization, the process by which electrons are removed from atoms of a material.[5, 6, 7] This process is especially apparent in plastics, elastomers, oils, grease, glass, and ceramics, but atomic displacement also occurs when atoms of materials are displaced by miscellaneous collisions. With metals, for example, the sun acts as an electromagnetic radiation (photon) source emitting infrared, ultraviolet, and X-rays. One approach to insure the reflection of this solar radiation is to use titanium dioxide (white paint pigment), although aluminum oxide has less tendency to yellow. Glass containing cerium is also quite resistant to neutrons, gamma radiation, and ultraviolet rays, and high purity fused silica has strong resistance to sunlight. Although polymers lose much of their strength through decomposition, becoming brittle and flaky, they can be protected by opaque coatings (aluminum or polyethyl film).

B. Preliminary Design and Fabrication Concepts

Articulating sections of rigid material that coincide with body segments, flexible joint areas, convolutes, and restraints for increased mobility were analyzed. An exterior layer of a rigid material was considered first, since it would provide adequate protection against abrasion, micrometeorite puncture, tears, and certain types of radiation. However, because of the potential difficulty in the fabrication of new materials, excessive bulk and anticipated mobility problems, this concept was rejected and the following design chosen.

The undergarment was woven in two layers, 100% Dacron® on the skin side covered by 100% worsted wool. Ventilation ducts (fig. 1) of extruded Omni with metal coils were used for delivery of gas for breathing and for thermal heat balance. This distribution system originates at a single inlet and follows the body contours to the head and extremities; the gas washes over the body and is dumped at one point in the waist area. The gas is contained in dual bladders of puncture resistant Omnicloth® separated by a pressure differential of 20 in. H_2O. Since the primary gas container would be exposed to the greatest amount of stress in areas where maximum flexibility is required, it was supplemented by silicone molded convolute with modified Link Net® (figs. 2 and 3). Omnicloth, a compound composed of fluorinated elastomers (VF_2 plus HFP), vinylidene fluoride, and hexafluorapropylene modified girconium tetra fluorethylene complex (gamma) copolymers, was selected as the basic material to be used for the bladder for the following two reasons. An environmental suit of this material had been used extensively in a vacuum of about 10^{-3} mm Hg pressure with temperatures up to 300 F, and this fabric is resistant to many strong and weak acids, alkalis, organic solvents, and missile propellants. Stainless steel wire was originally considered for fabrication of the exoskeleton Link Net support structure for the double bladders. However, HT-1 Link Net was used instead when stainless steel wire was found to take a set when a load is applied and will break after repeated flexing under load. The broken ends would then abrade or puncture the bladder.

The HT-1 fabric is constructed of specially processed nylon fibers, i.e., Nomex®, 200 denier, which have superior physical properties, are nonflammable at the anticipated temperature extremes, have a high stability factor within the expected lunar environment, are abrasion resistant, and more than adequately withstand stresses applied at 12 psi.[6] Because of these characteristics, this material was used in the inner restraint, thermal protective coverall, Link Net restraint layer, webbing, and threaded seams.

The thermal and radiation protection begins with a layer of 1/8 in. open cell silicone foam coated with aluminum applied by the transformation method. This is followed by a thin layer of Teflon® fabric to which small 2 in. by 2 in. or 3 in. by 3 in. formed plastic (phenolic or polyester) plates are attached. These plates provide radiation and high velocity missile

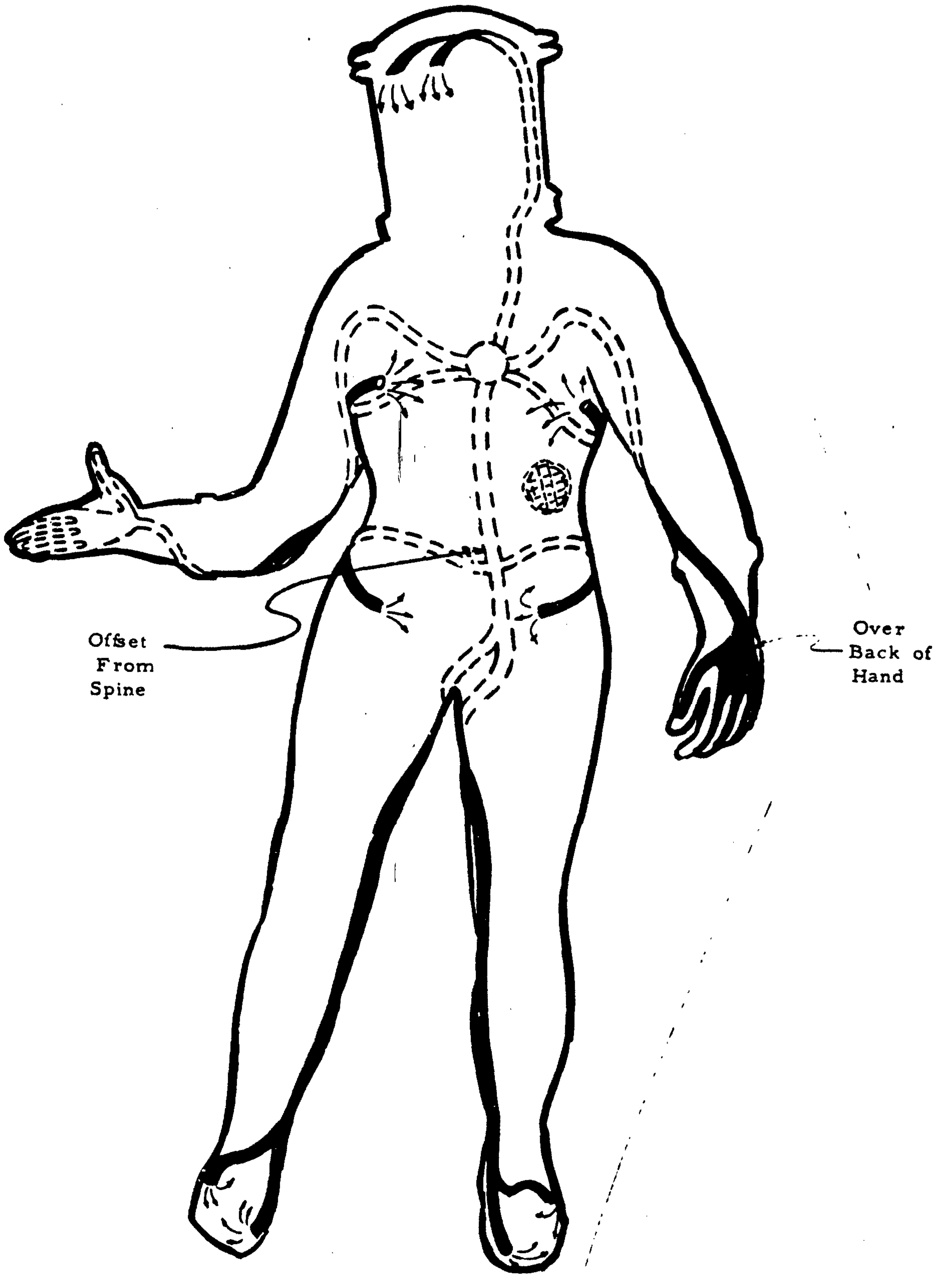


Figure 1. Ventilation Duct System

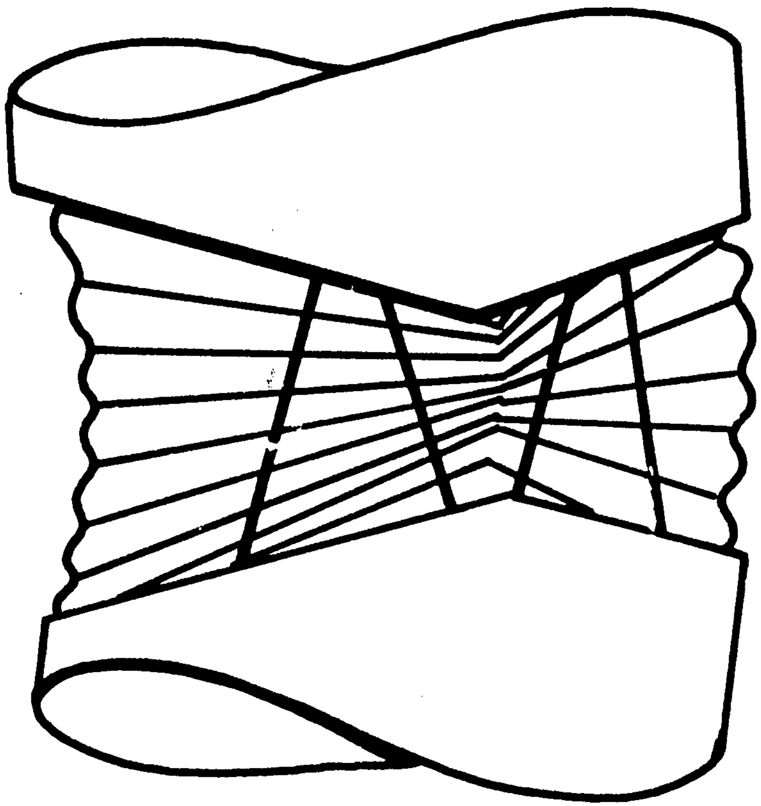


Figure 2. Silicone Molded Convolute with Modified Link Net

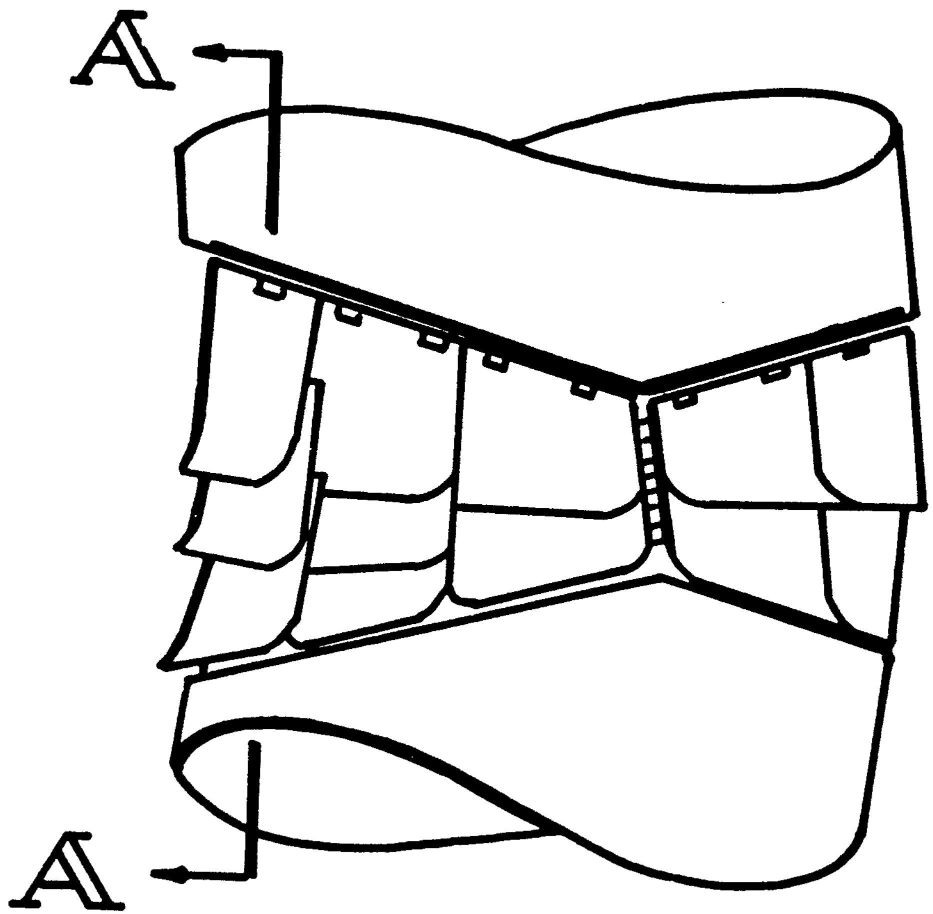


Figure 3. Typical Joint Shielding

protection (fig. 4). After a short period of outgassing of trapped air, this becomes a superinsulation in a high vacuum environment with the high density metallic layer reflecting radiant thermal energy, while the foam portion insulates against conductive heat transfer.

The body of the pressure assembly was completely protected by a strong, flexible, abrasion and puncture resistant Omni- and aluminum-coated fabric, thus obtaining 75% reflection plus additional abrasion and vacuum resistance. Also, the exterior layer has rigid sections between limb joints and the front and back torso which act as protection against missile impacts and certain types of radiation.

The torso closure consists of helical flat coils molded into a flexible butyl, silicone, and Omni encasement (fig. 5). The closing operation is accomplished by manually cranking an easily accessible gear mechanism which drives a flexible cable that picks up the helical coils. This new closure concept incorporates continuous interlocking coils, spaced so that a locking shaft can draw the two sealing surfaces together. A drive system, consisting of a gear box and hand crank, conveniently located for the subject, feeds the shaft at a closing rate which overcomes the problem of closing a slide fastener on a reasonably close fitting suit system. Blowout protection is provided by this device since, even though one coil may become broken, the closure does not fail. (With the chain zipper, however, a tooth failure could be catastrophic.) Self-donning within acceptable time limits, under conditions other than weightlessness, was believed possible with this new-type closure.

Also included in the initial design was a cylindrical shaped helmet made from either stainless steel or titanium in a double-wall construction with an approximately 1/16 in. separation to allow for circulation of thermal control fluids (fig. 6). A visor or lens of high temperature glass thermo-pane construction with a Calrod-type heating unit in the outer surface of the lens was proposed since double curvature of the glass was not required. A spray bar around the inner surface augments the defogging capabilities of the heaters. The use of a filtered glass glare shield, which would track over the thermopane glass lens, governed by a light-sensitive photoelectric cell was also considered. This shield or phototropic film would automatically darken upon exposure to a certain degree of brilliancy and then automatically lighten again within 2 seconds after removal from the light source. This phototropic action is uniform in the direction of the illumination and is achieved through the chemical change activated by the radiation energy. Buffet protection was provided by a pneumatic cell-type structure with an outer covering of segmented 1/2 in. thick, 2-1/2 lb. density Ensolite® sponge. This structure was placed as close as possible to the inside of the dome wall. Pressure sensitive switches were located strategically throughout the inside of the dome to activate cells at a rate determined by the rate

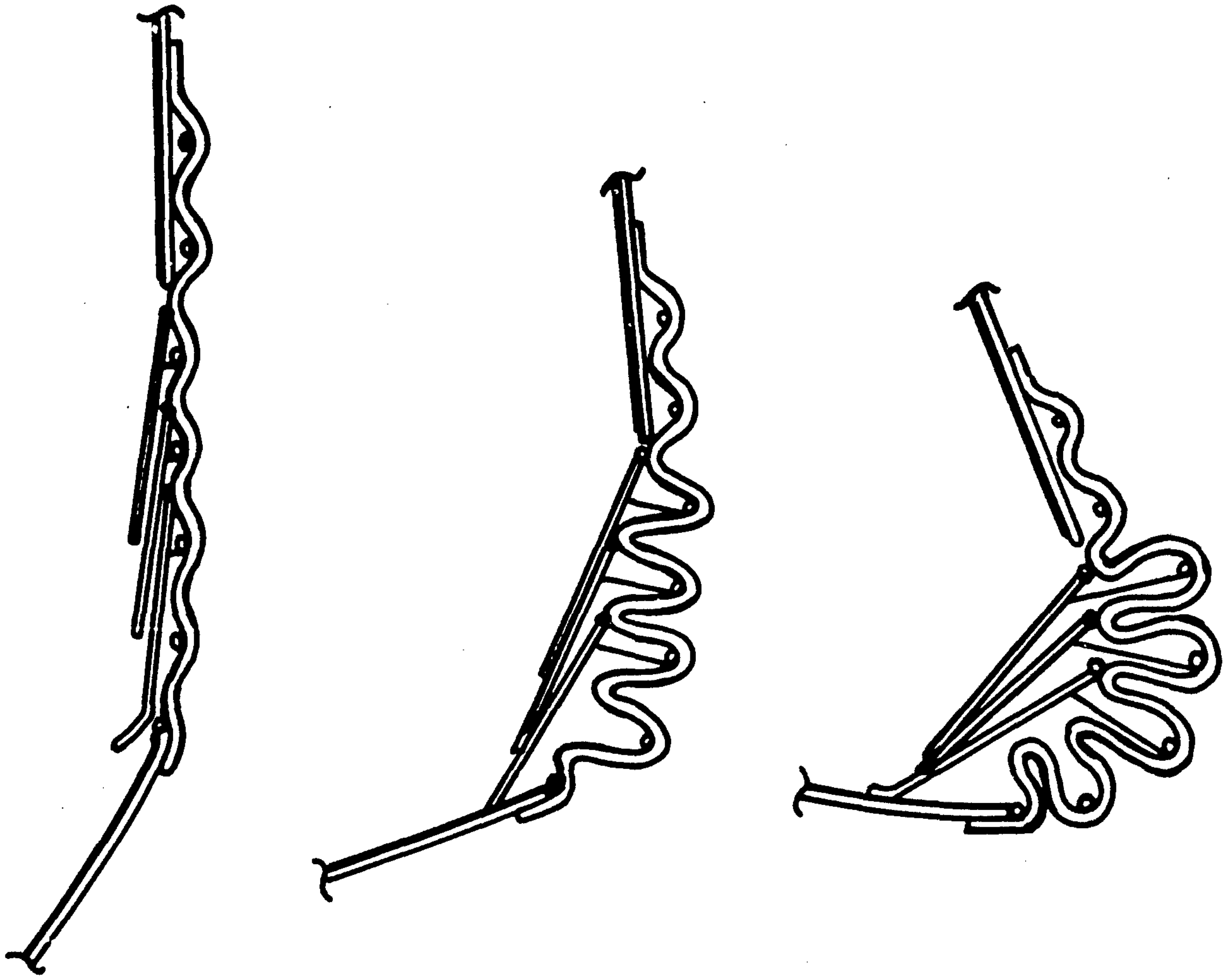


Figure 4. Plastic Plates Attached to Teflon Fabric

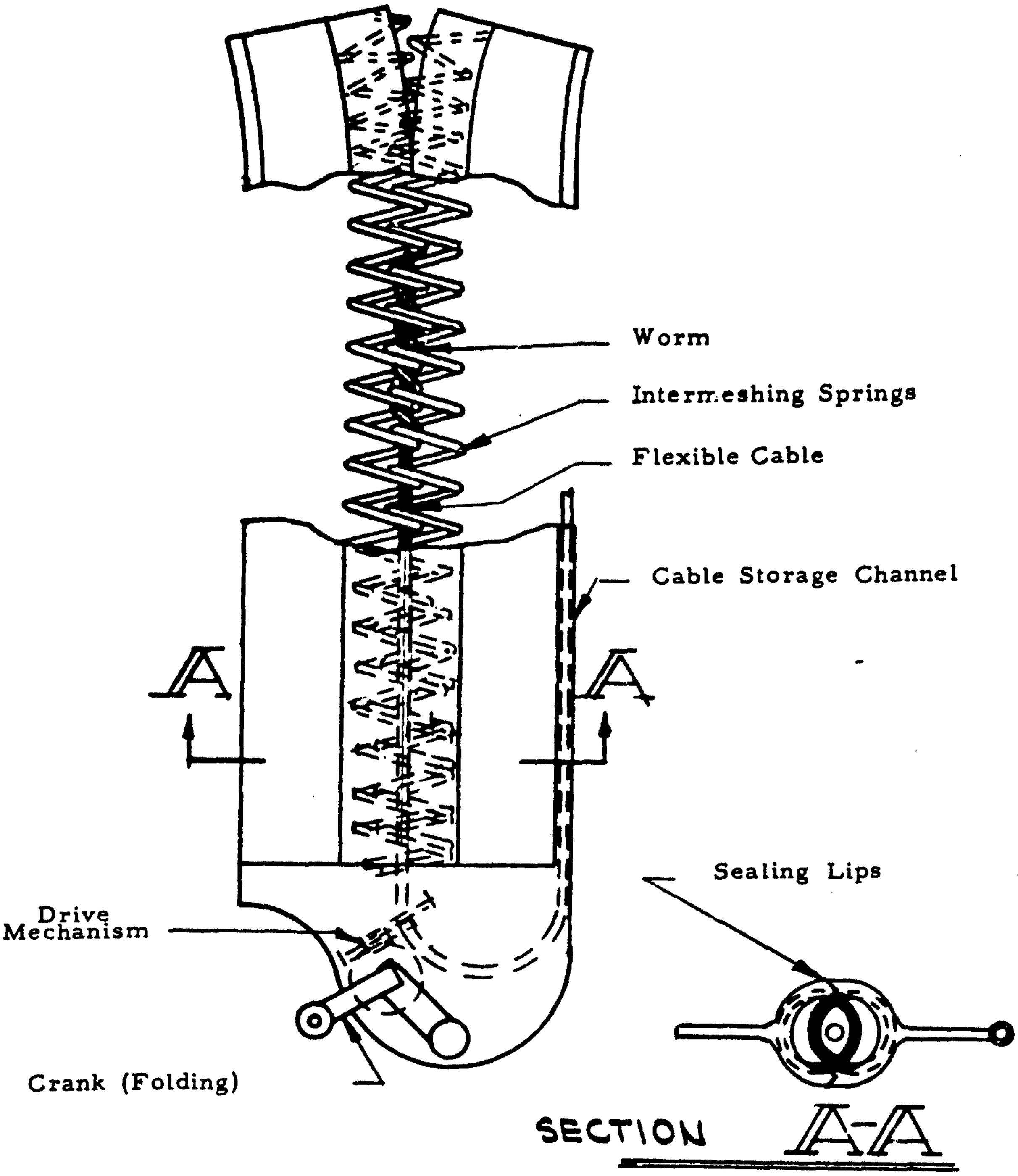


Figure 5. Pressure Sealing Torso Closure (Proposed)

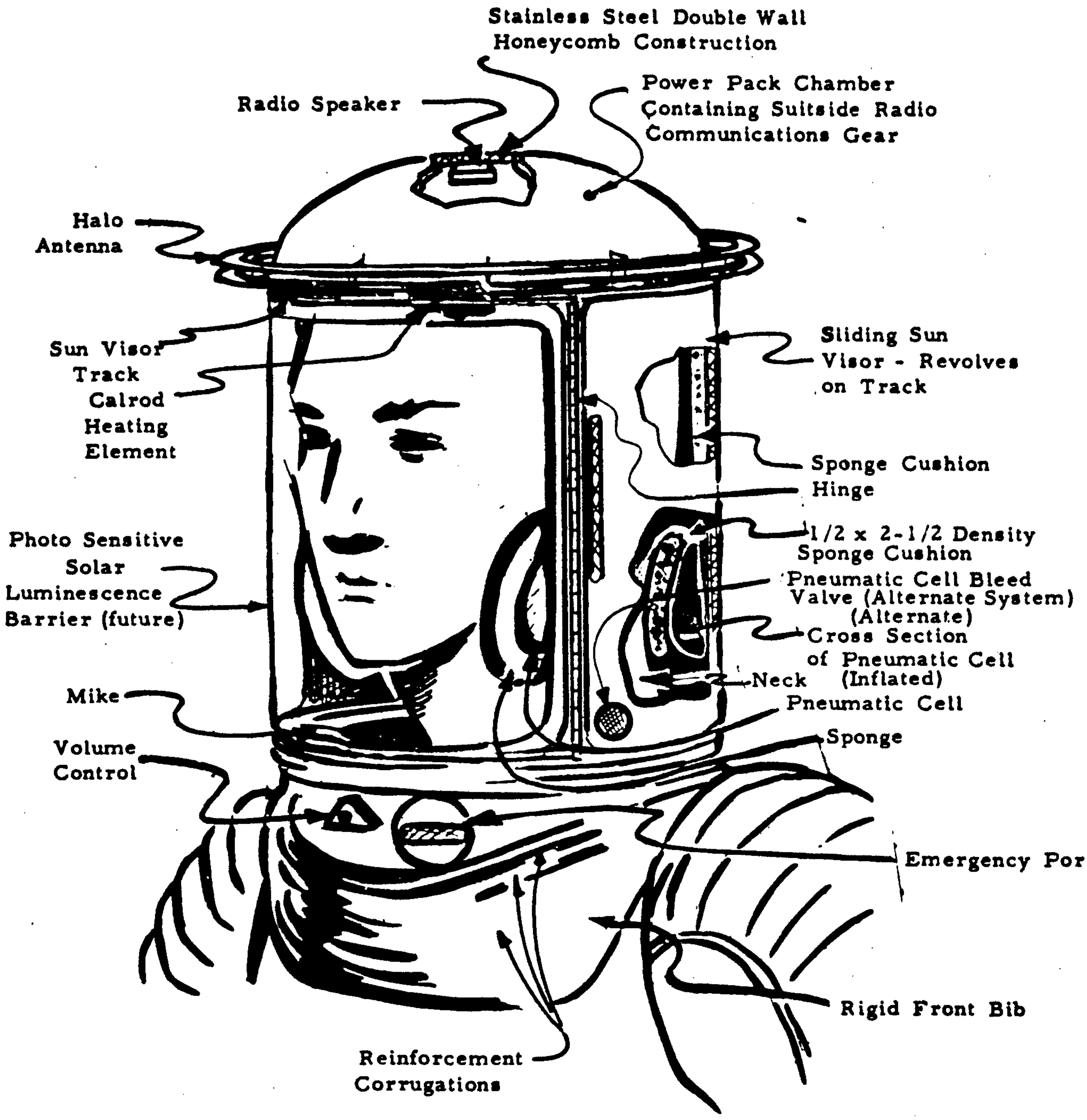


Figure 6. Head Enclosure (Proposed)

of impact. Activated cells then locked the subject's head in position with a sponge cushion until the buffeting stopped. At that time, cells were deflated by means of a manual bleed-down button located on the exterior of the dome wall. Light buffeting was absorbed by a segmented sponge cushion on the inner dome wall and exterior of the pneumatic cell. A CO_2 warning device was proposed for installation in the face area of the helmet, and communication equipment compatible with AMRL test facilities communication equipment installed in the assembly. The boots and gloves were similar to current designs with the addition of the torso layer insulation described on p. 7.

SECTION III

PROTOTYPE DESIGN

A. Changes in Material

Except for the visor, the materials discussed in Section II, A, remained unchanged. Both their use and the reasons for changing, however, are more fully described in the following paragraphs. Most of the materials selected had never been used in this manner before and presented several problems even though extensive laboratory work had been conducted. An effort was made to initiate procurement of fabrics, hardware, compounds, etc., with long lead times. Much of the fabric material (or combinations) was new and special manufacturing processes were required. Standards were established for all of the material to be used. Some materials were most difficult to obtain in the required quantities even though small quantities were easily obtained and test runs had been made for evaluation.

B. Design Changes and Fabrication Techniques

As material selections were made, their application to the assembly was clarified resulting in a more definitive design of each particular section (figs. 7 and 8).

The undergarment, vent duct, and primary bladder designs remained generally unchanged from those described in Section II. This suit concept required soft material extending from the top of the shoulder to the top of the helmet. The entry opening began in the groin, passed through the crotch, and extended up the back through the soft helmet to the back center of the head. The overall restraint layer of Link Net construction was supplemented by a breastplate of stainless steel or molded high strength plate (fig. 8). The hard sections were used in this and other areas for meteoroid protection. The neck yoke was permanently attached to this plate and the restraint material secured to the edges of the plate. The same rigid material was used in the back torso, split at the back center, and attached to the pressure sealing closure on both sides. Eliminating the restraint fabric under these plates controls the desired contours and eliminates feeding the material into other areas of the suit. Both back sections were hinged to the breastplate on the sides to enable the suit to be spread for entry and egress.

The areas of the suit, such as the shoulder, elbow, knee, and hip, where extreme flexibility is required have convolutes of molded silicone and controlled Link Net (fig. 9). The convolutes were installed over the shoulder and on the inside of the upper arm below the armpit to insure

Figure 7. Front View of Exterior

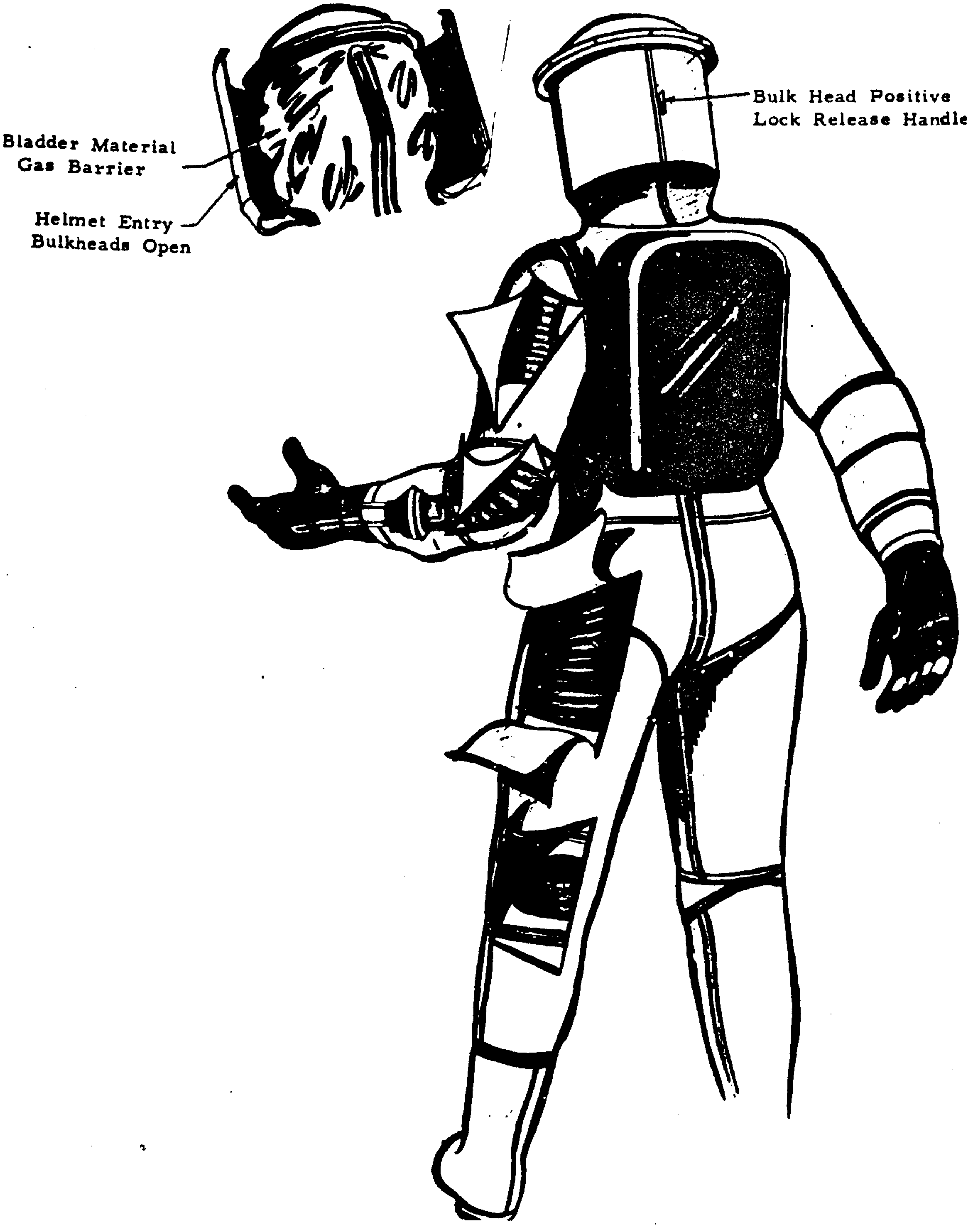


Figure 8. Rear View of Exterior with Backpack Secured

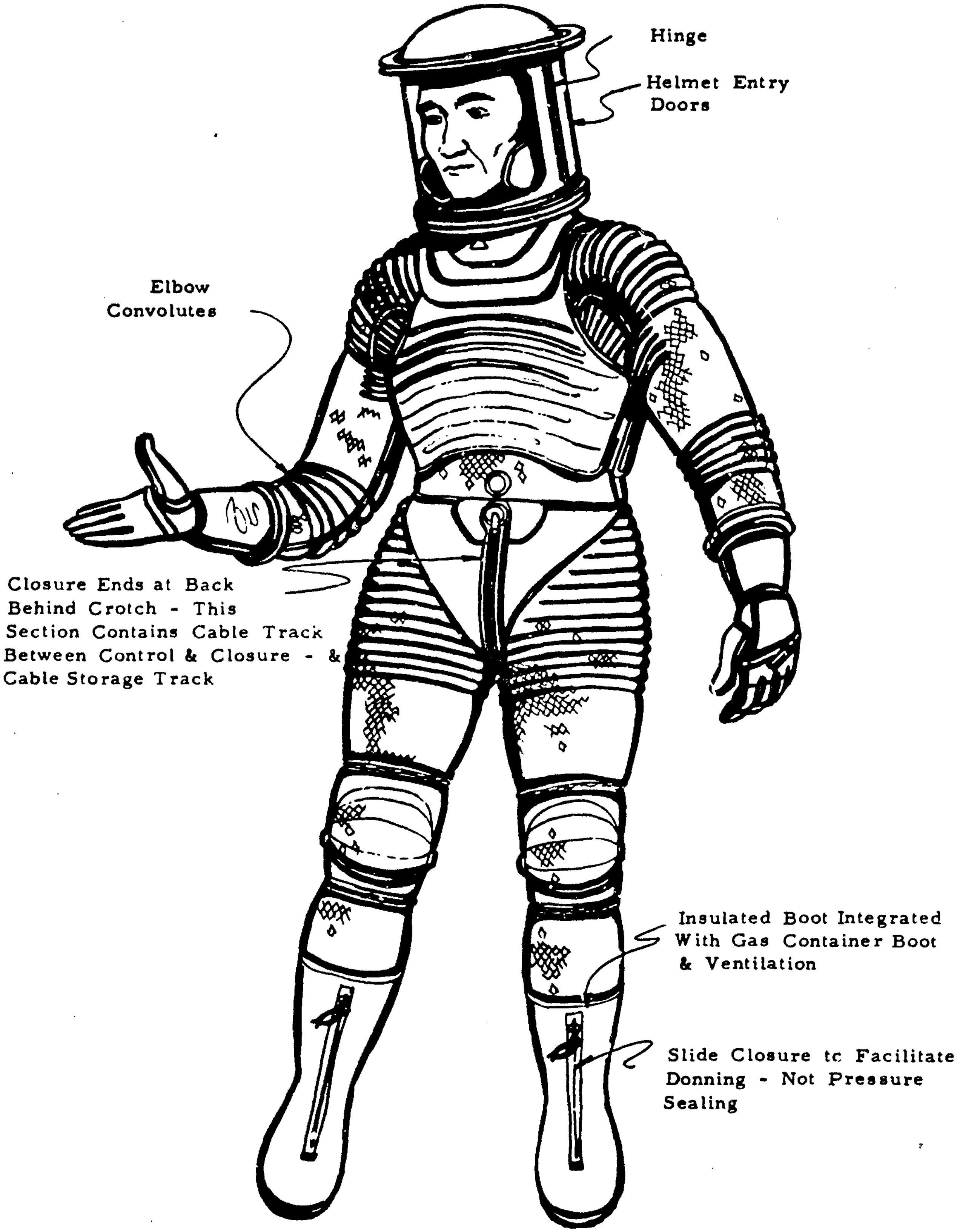


Figure 9. Front View of Restraint

a minimum amount of bulk material in the armpit area. The elbows were basically the same with the convolutes restrained on the inseam and outseam of the arm. The hip area was similar with an additional restraint line passing through the convolutes at the inseam and outseam of the leg. The knees had the same configuration as the elbows with the addition of a hinged rigid material pivoted at both sides of the joint. The front and back knee areas were open to allow freedom of movement of the Link Net convolutes. This type of construction provided a definite pivot point for the knee.

Biological monitoring and data collection were provided for by the use of a 24-lead connector incorporated in the suit. Suit absolute pressure and vent system resistance gages were used, plus a carbon dioxide color warning patch.

Working models of pressure sealing closures were fabricated in short lengths and performed satisfactorily, but the long length required by the pressure assembly could not be achieved. As a result, the B. F. Goodrich Type 1430 standard pressure sealing closure was used in the torso to close the gas container and the restraint layer. With the use of the 1430 pressure sealing closure, self-donning capability was sacrificed. The opening then extended from the groin through the crotch, and up the back to a point between the shoulder blades.

The dome was as nearly cylindrical as possible with a hemispherical top. The basic material was 0.27 and 0.32 Type 304 stainless steel to meet the strength requirements and constructed in a manner that would enhance the stress and structural value with a minimum of weight.

The thermopane safety glass visor with the Calrod heater units was ordered from a glass manufacturer. However, after further negotiations, we were advised that they would be unable to fabricate the article. A new plastic, Bavick II, selected for its strength to weight ratio, was obtained for molding into the desired lens shape.[8, 9]

Even though the manufacturer's procedures were followed, forming of the visor or face piece from Bavick II (Solplasco) presented some problems. It was not possible to form a satisfactory lens using the manufacturer's time and temperature curves. When subjected to the recommended temperatures in a forced hot air oven, bubbles occurred throughout the sheet caused either by moisture or air entrapment (fig. 10). Another series of tests was conducted in an attempt to eliminate the problem. Two pieces of Bavick II, 4 by 4 by 3/16 in. in size, were placed in a drying oven in various ranges of time and temperature prior to heating for the final forming cycle. After several tests, a satisfactory drying cycle of +66 C (+150 F) for 15 hours in a forced hot air oven was established.

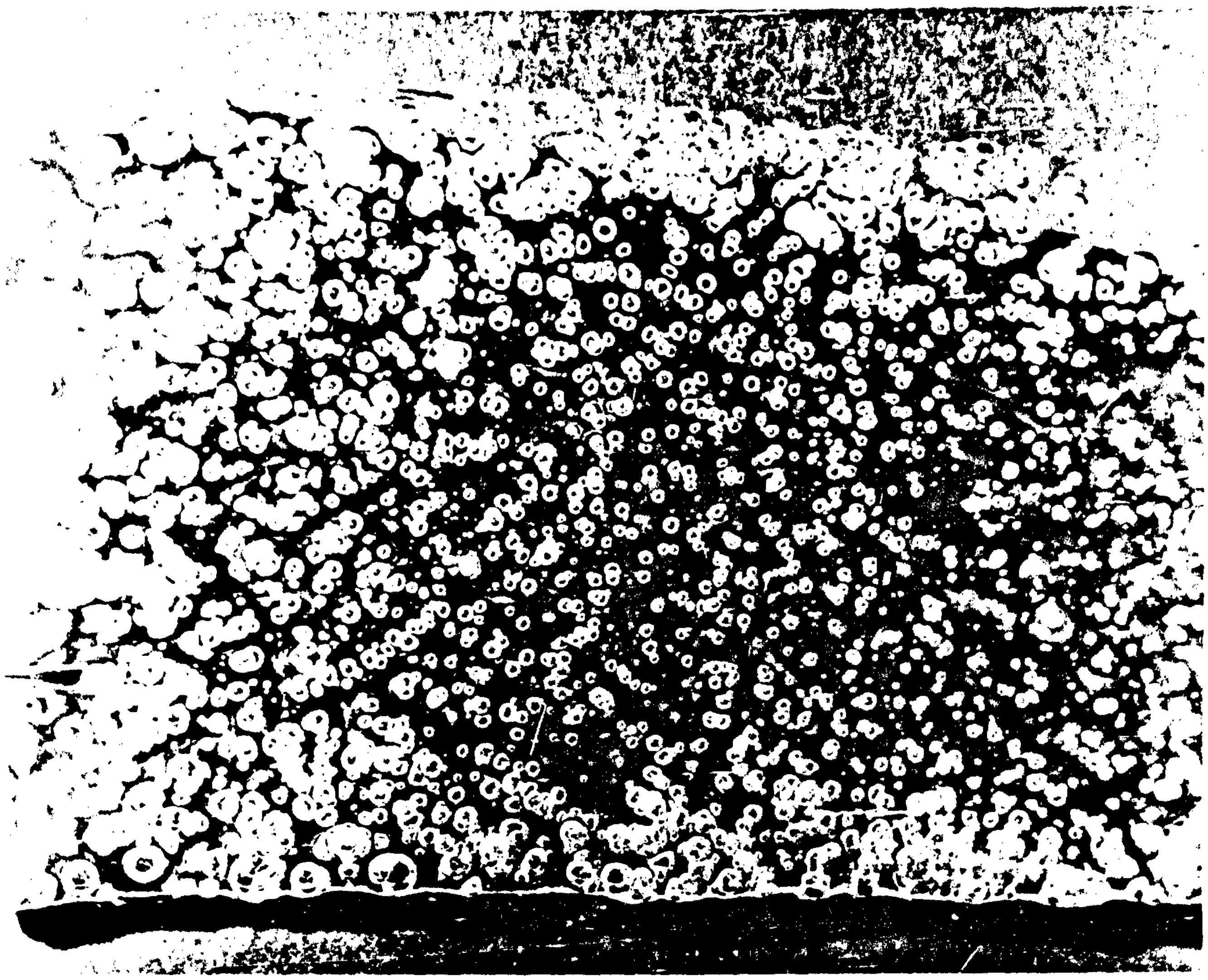


Figure 10. Bavick II, Bubbles Developed in Forming Visor

A sheet of 27 by 18 by 3/16 in. Bavick II was clamped to the forming jig and placed in the oven at +182 C (+360 F) for 6-1/2 min. Upon completion of the heating cycle, the jig was removed from the oven and placed over the vacuum mold and drawn to final shape.

The lens was allowed to cool slowly at room temperature before removal from the clamping frame. The lens was then attached to a normalizing jig and placed in a hot air oven for 24 hours at 150 F to anneal and relieve stresses incurred during the forming cycle. Restoring the lens to optical clarity was accomplished by using standard sanding and polishing procedures. Loss of clarity occurred in the forming operation due to the type of molds being used. The lens was then placed in normal storage until it was to be attached to the dome. About 10 days later, the lens was removed for a dimensional check and a form of degradation was observed. This consisted of cracking and splitting of the material at the lens periphery and inboard as well (fig. 11). The material manufacturer was consulted without obtaining a satisfactory solution to the problem. Further investigation and study were halted and plans for using this material in the assembly were abandoned.

Development and design of the glare shield to provide face protection from brilliant illumination, ultraviolet, and infrared exposure discussed on page 7 was not included since this item was currently under investigation elsewhere. A glare shield (fig. 12) of Plexiglas No. 2 UVA, color No. 2247, was molded to be compatible with the helmet assembly as a substitute for the phototropic glare shield.

Light antibuffeting protection for the head was provided by segmented 1/2-in. thick, 2-1/2 lb. density, Ensolite sponge. This material was so constructed that it would stay as close to the dome wall as possible to provide maximum head protection. Any one of several pressure sensitive switches, placed strategically throughout the inside of the dome, activated the cells at a predetermined rate of impact. The cells, with sponge on the outer surface, were inflated with suit supply oxygen, holding the subject's head in a locked position until the wearer desired to deflate the cells. This was accomplished by means of a manual bleed-down button mounted on the dome's exterior.

The problem of properly insulating the dome interior was investigated in great detail. The original approach, incorporation of a double stainless steel shell with coolant fluid circulated between the layers, was abandoned due to the amount of time and research needed to achieve success. An alternative approach was evolved which resulted in a liner which covers the complete interior of the helmet excluding the visor area.

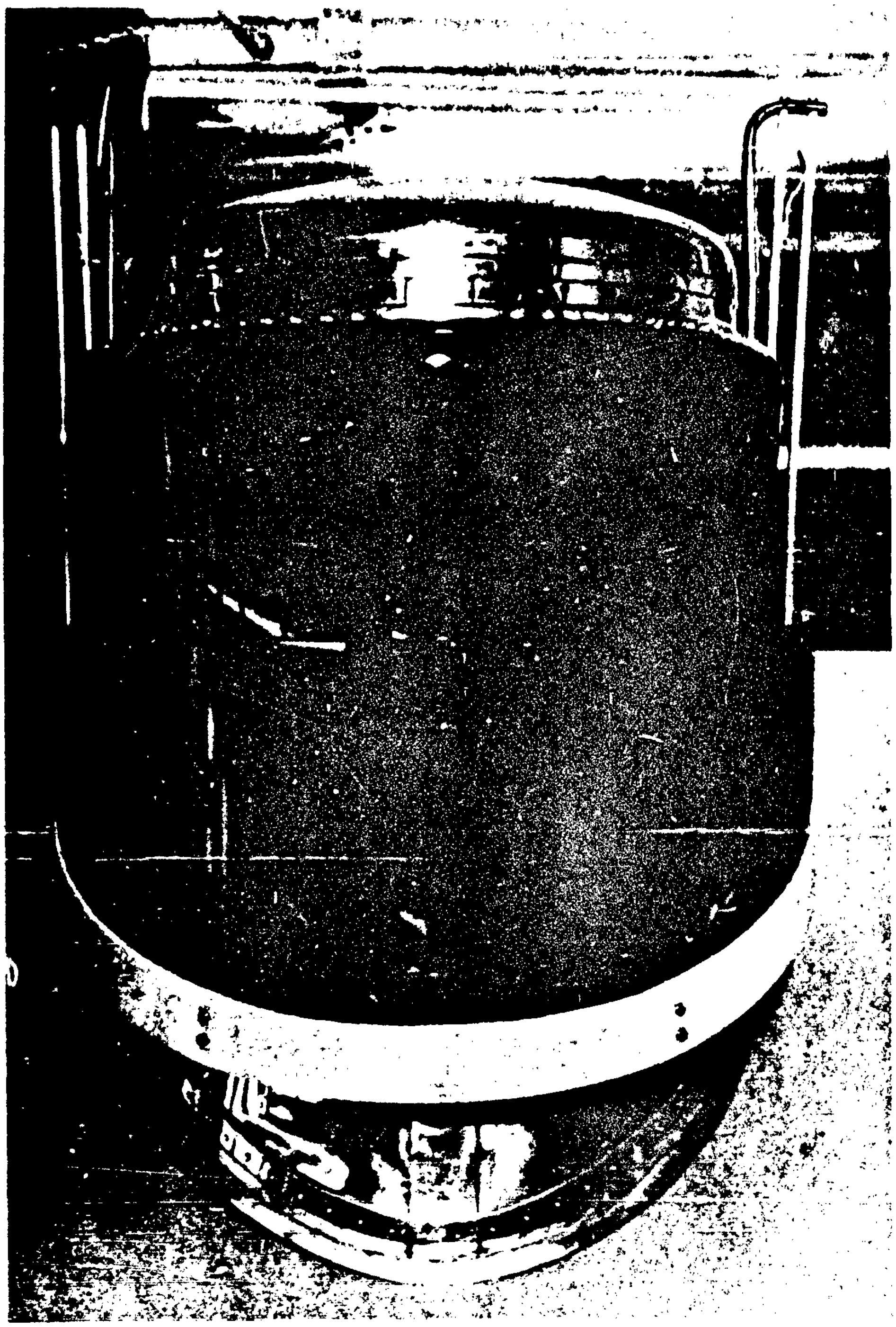


Figure 12. Visor Glare Shield

A carbon dioxide indicator was intended to alert the subject when the CO_2 build-up in the dome reached upper safety limits. However, efforts to obtain commercially or to fabricate a colorimetric type device, such as Baralyme, were completely unsuccessful and further investigation was discontinued.

SECTION IV

CONFIGURATION OF THE FABRICATED ITEM

A. Materials Selected

To reduce excessive weight, the rigid sections of the torso assembly were eliminated in favor of ballistic nylon felt. While this is recognized as being inadequate protection for a space traveler against hypervelocity impacts, it is nevertheless an improvement over current pressure suit capabilities. The material of the gas container was changed from Omni coated HT-1 fabric to P-1807A material. This change was due to the failure by separation of the fabric from its coating during proof pressure testing at 12 psig for 30 min. The P-1807A bladder material is similar to that used in the Dyna Soar and AP/22S-2 protective assemblies.[10,11] The visor material, Bavick II, did not respond properly to forming techniques and it was necessary to fabricate the lens of 2 UVA Plexiglas. This material is used in the HGK-13 and Dyna Soar face plates or visors. Details of the technique used and difficulties encountered are discussed in the following paragraphs. The materials used in the final configuration are as follows:

Double knit 100% Dacron - 100% worsted wool
Mercerized cotton
Bladder Cloth TDA
HT-1 fabric - Omni coated (feet only)
HT-1 fabric - treated - 32-lb. test
HT-1 thread (size E)
Mylar - aluminum coated
Leno - high tensile strength nylon
Graphite fiber fabric
Ballistic nylon felt
HT-1 fabric - aluminized
Stainless steel - helmet
Special oxygen hose - Redar® A80401-8
Leather - helmet
Foam - helmet
Neoprene - slide fastener
Tri-lok ®
Aluminum - wrist disconnects

Figure 13 illustrates the use of these materials.

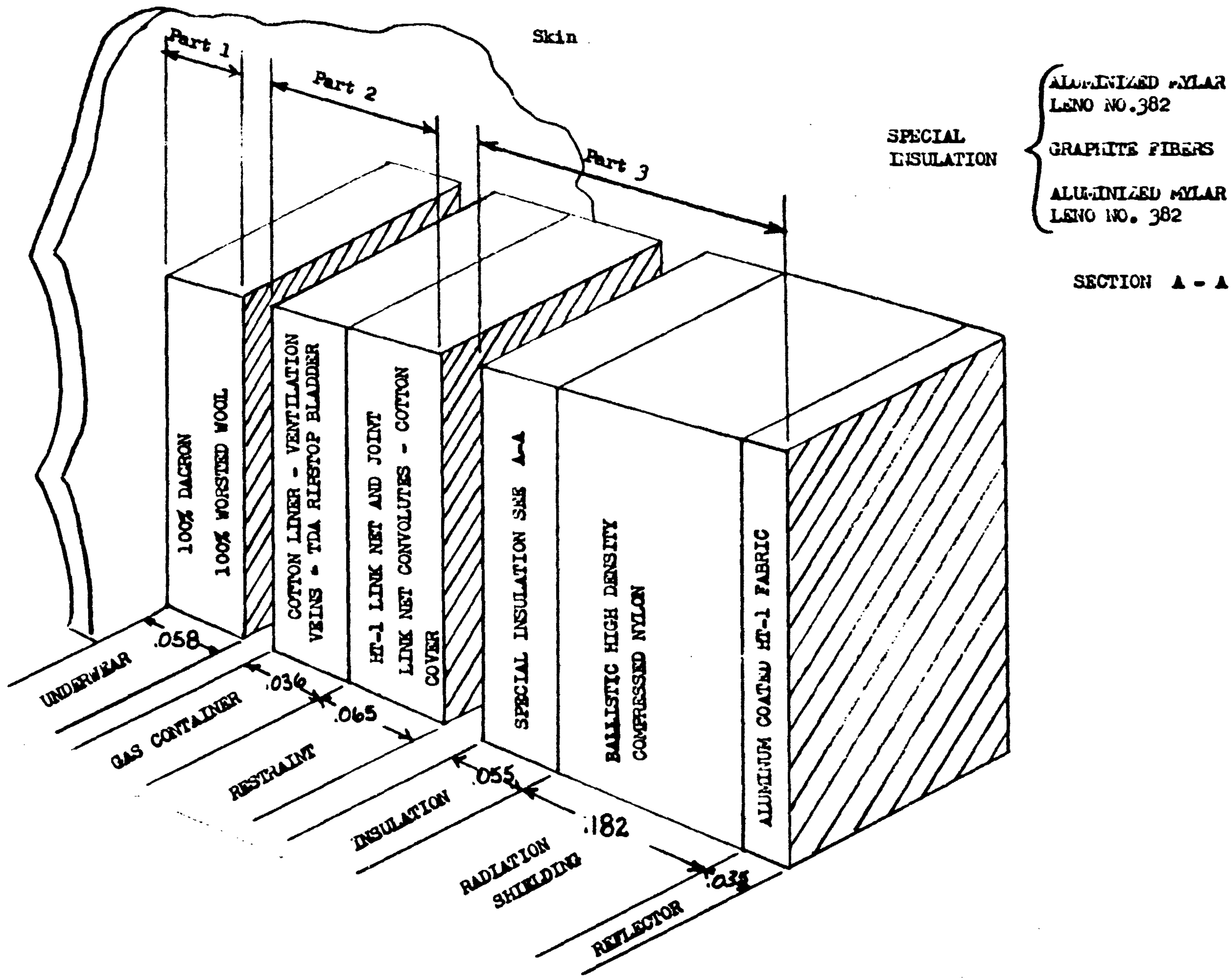


Figure 13. Materials Application

The penetration resistance of felts has been investigated by the U.S. Army Quartermaster Research and Engineering Laboratories, Natick, Massachusetts. Their studies indicate Ballistic nylon felt to be the best impact-protective material known today. Ballistic values based on work with a .22 caliber 17 grain (1.1 gram) fragment simulator are as follows: for a 3/8-in. thick felt with an area density of 6.5 oz/ft^2, V_{50} = 1100 ft/sec and for 1/8 in. thickness with an area density of 2.2 oz/ft^2, V_{50} = 790 ft/sec. Ballistic nylon fabric, one layer thick (0.028 in.) and having a V_{50} = 350 ft/sec, was also considered. Further information concerning ballistic materials can be obtained directly from the U.S. Army Quartermaster Research and Engineering Laboratories, Natick, Massachusetts.

Potassium titanate asbestos was originally planned for use as the main insulation material, but during the first fabrications of this new material it was found to be too brittle and shattered easily. The insulation layers of aluminized Mylar and nylon Leno sandwiched with a graphite fabric were retained. The Leno serves as spacers between the reflective surfaces of the aluminized Mylar. These layers were so designed that in a high vacuum after short periods of outgassing this area becomes superinsulation with a high density metallic layer reflecting radiant heat thus resulting in a thermal energy balance. At the center of this package is a graphite fiber acting as a balance and shield for conductive and convective energies (fig. 14). This insulation package was designed to provide temperature resistance up to +500 F ambient. Laboratory tests indicated that the temperature differential through the package was 340F during the 4-hour test at 26 in. of Hg pressure. Flexibility of the insulation is good even with the expected high coefficient of friction in a vacuum and the adhesion from the high surface cleanliness. The area of contact is small because of the Leno and low force is capable of breaking any adhesion. The insulation package is backed with mercerized cotton fabric because it is lighter in weight and has greater resistance to wear and tear than the Helenca® fabric originally considered for this application. The present insulation is based on a 500 Btu/hr output of the subject and is capable of handling four times this amount or 2000 Btu/hr.

B. Final Design and Assembly Techniques

The failure of the HT-1 fabric with Omni coating during overstressing tests could not be corrected by recoating and recuring. Though the leak rate through the fabric was reduced by this action, the rate was still excessive -- 50 lpm at 5 psig. No difficulties were encountered in fabricating the replacement bladder of P-1807A material, however, the measured leak rate for which was 0.65 lpm at 5 psig.

The restraint layer was fabricated from Link Net. Although patterns had been developed for other pressure assemblies using Link Net made

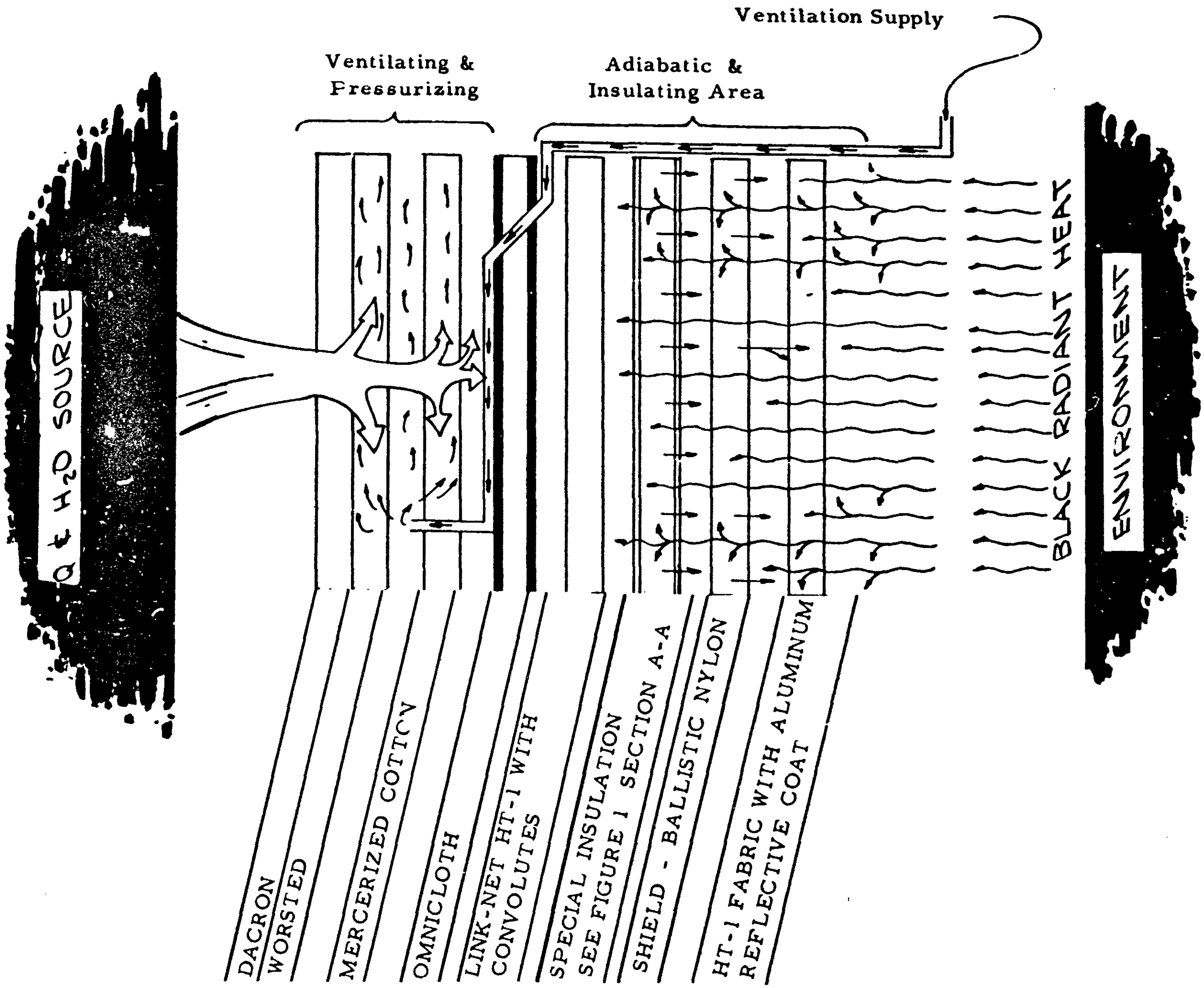


Figure 14. Suit System Functional Chart

from nylon and Dacron, the same patterns when applied to the HT-1 line did not achieve the same results. Basic Link Net construction is a series of parallel cords which loop each other at frequent intervals. There are no knots in these loops, and the cords are loose so that they can slide over each other and feed from one suit section to another. This action allows the suit to deform easily under the influence of forces exerted whenever a subject alters his body position. The use of this material in pressure assemblies is to provide maximum mobility and a restraint for the bladder. The theory underlying construction of this layer involves shortening/lengthening characteristics where the circumference change is directly proportional to the length change on the 20 to 370% basis. In other words, the length stretch is far greater than the circumference stretch. The flexibility and slipperiness of the net on the gas container is most important in establishing and limiting the amount of torque required to twist a sleeve.

In areas where too much was apparently being expected of the one restraint layer, an inner restraint was installed between the gas container and Link Net to accept the major restraining load and partially relieve the net of excessive stress. This allows the net to move more freely to those areas, such as arm contours, knees, and elbows, according to the demand of the wearer. Restraint cords tied over the layers create slight convolutes causing the net to bridge. This bridging relieves an undetermined amount of friction and allows easier Link Net movement (fig. 15). Net slides more easily on the surface of the inner restraint layer than on the bladder and also helps to keep the bladder from extending (figs. 16 and 17).

Plexiglas No. 2 UVA was selected for the visor lens when the Bivack II lens failed. Using estimated load requirements of the design profile, 1 inch wide construction samples of dome attachment and sections of lens material were assembled and subjected to a tensile load (Scott Tester). To provide adequate gasket clamping, a fastener spacing of 1/2 inch was selected on all bolted seams. With two screws to the inch, a force of 32 lb longitudinally and 16 lb circumferential load per fastener was obtained. Tensile tests of the lens material and cross section of dome attaching area were conducted. A 1-inch sample with one screw on the center line indicated a minimum breaking load of 120 lb force. Assuming that each fastener is equally loaded, the data indicated a minimum safety factor of 4 at 12 psig internal pressure. A safety factor of 8 is anticipated at operating pressures of 5 psig.

Based on the above referenced tests and data, a vacuum forming jig was designed and fabricated of Fiberglas and wood to exact dimensional tolerances to form the lens.

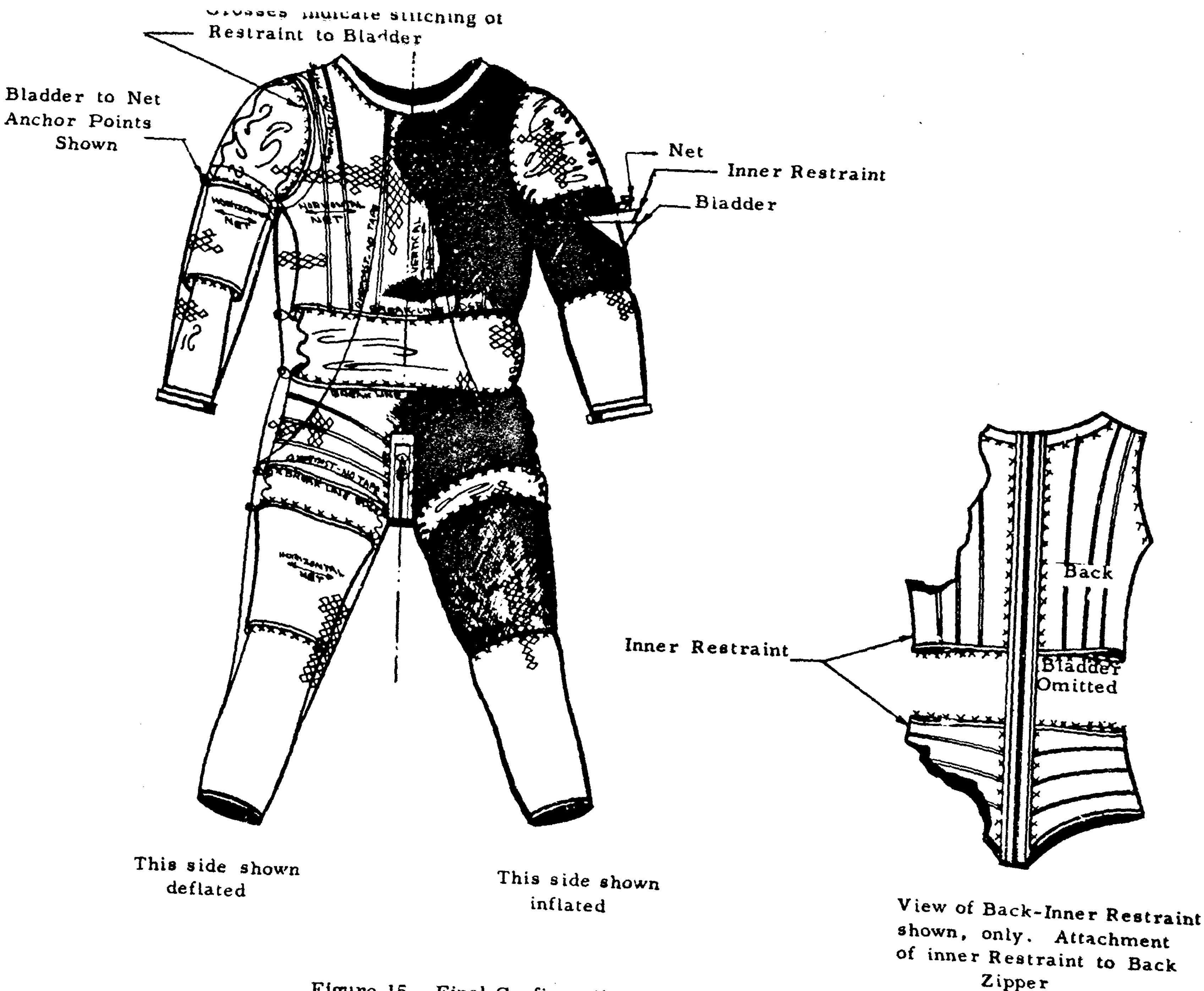


Figure 15. Final Configuration, Restraint and Gas Container Combined

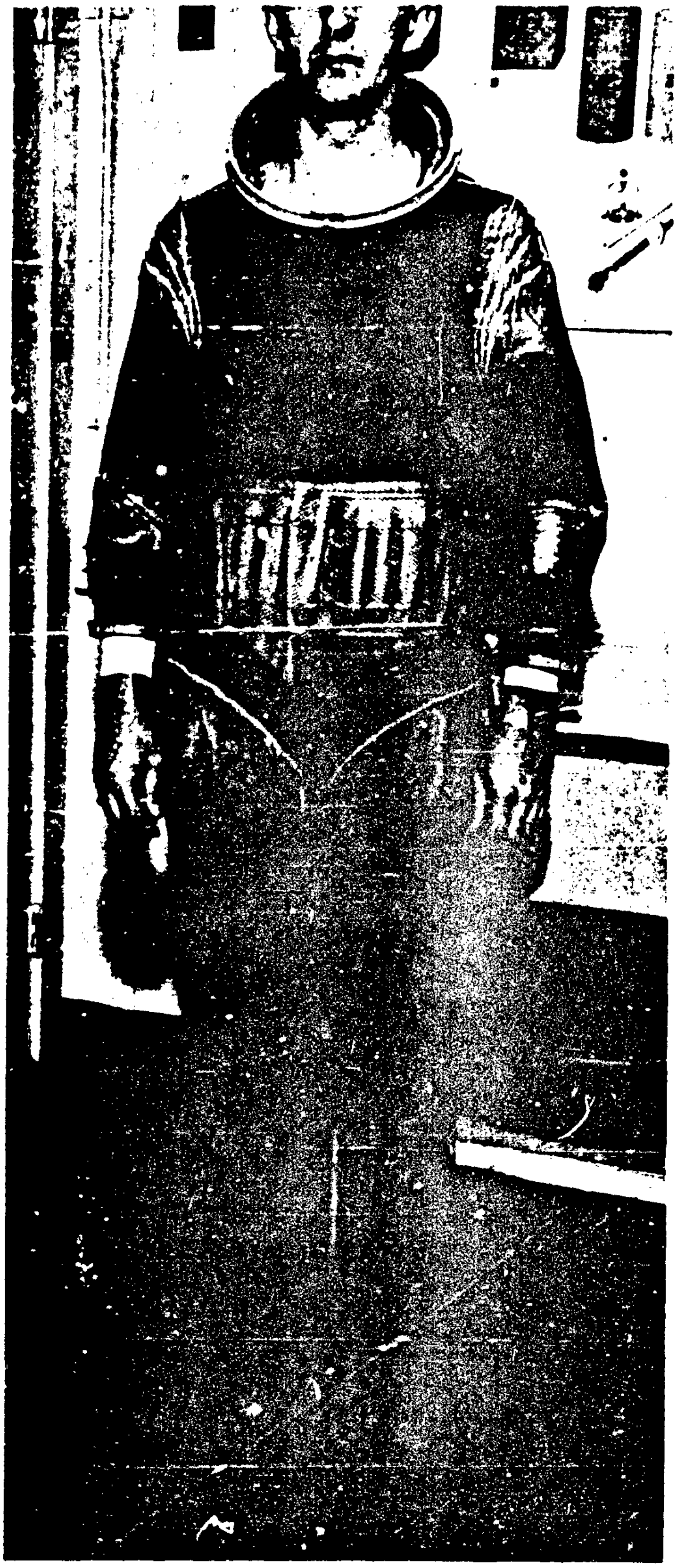


Figure 16. Front View of Restraint Layer

Figure 17. Rear View of Restraint Layer

C. Helmet Hardware Development

1. Spray Bar

The air-wash spray bar, originally intended as a supplemental defogging device to the Calrod heater in the safety glass visor, was fabricated from 48 in. length stainless steel tubing and 3/8 in. ID and attached to the periphery of the lens inside the dome by means of miniature hose clamps connected to the lens clamping frame. This tube was attached to the terminal ends of suit ventilation ducts at the rear portion of the dome. The flow supply emanates from two separate sources: one from the suit vent supply and the other from the liquid oxygen backpack boiloff line. The air-wash pattern is designed with hole size and spacing in the spray bar in a manner which permits maximum flow across the lens with a minimum of back pressure.

2. Liquid Oxygen Port

The boiloff time from the backpack to the dome interior required a positive seal and removable elbow port located in the right rear quarter of the dome. Construction details of this port are shown in fig. 18.

3. Oral Access Port

The dome and lens are basically not detachable and the design and fabrication of an oral access port was considered necessary for emergency purposes. This area is not intended for feeding purposes, but as a manual antisuffocation type opening for ground operation (figs. 19 and 20).

D. Final Construction Details

The construction of the completed assembly (fig. 21) consists of the inner layer of underwear, the torso gas container with integral helmet and feet, gloves, overmitts, inner boots, outer boots, and the outer protective coveralls (figs. 22 and 23). The materials listed in Section III, A and B were used in the following areas of parts of the final construction:

1. Body Covering (exclusive of hands, feet, and head)

   a. Inner Layer or Underwear - knitted garment of 100% Dacron and 100% worsted wool

   b. Middle Layer or Gas Container

Figure 18. Elbow Fitting and Access Port

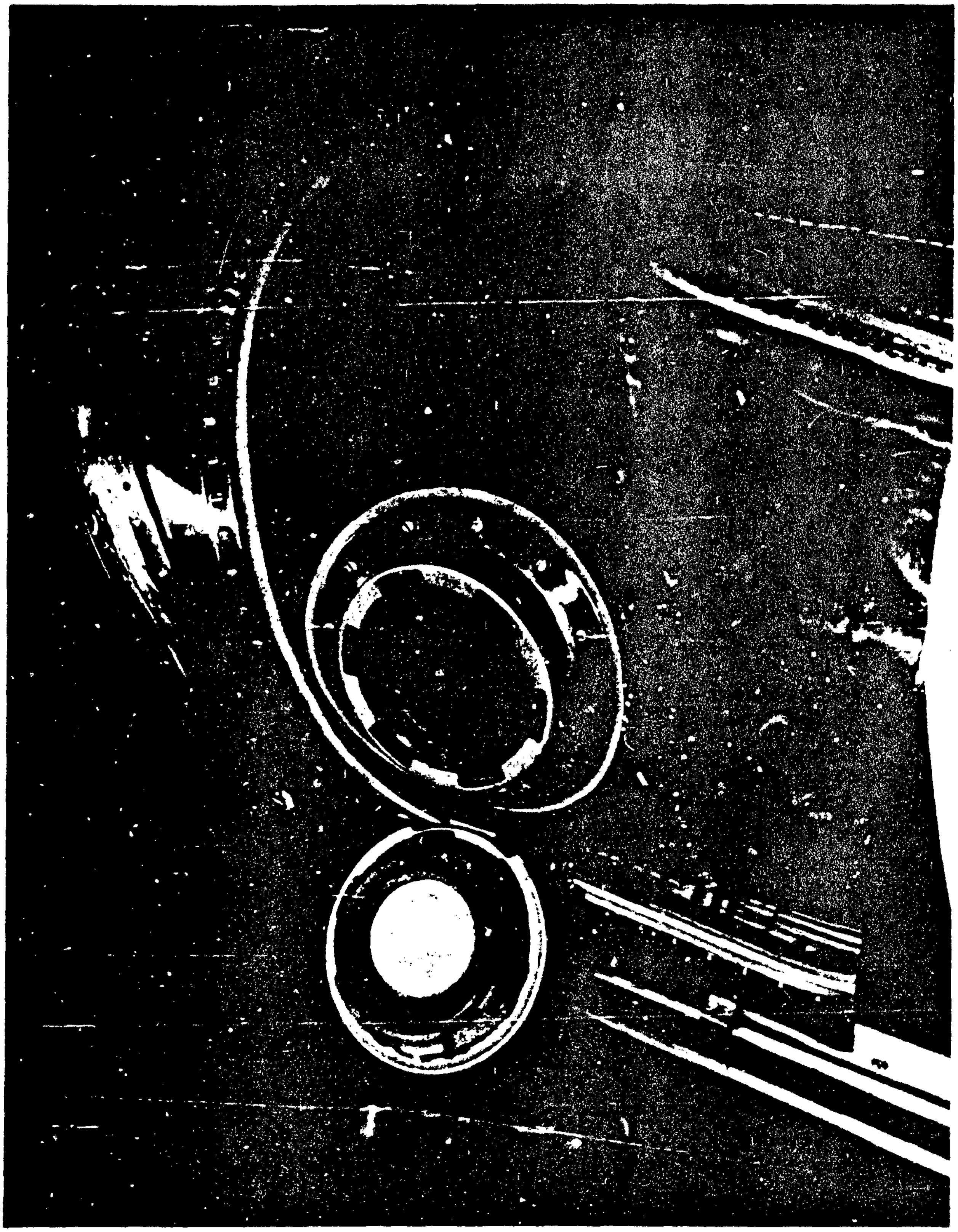


Figure 19. Exterior View of Antisuffocation Port

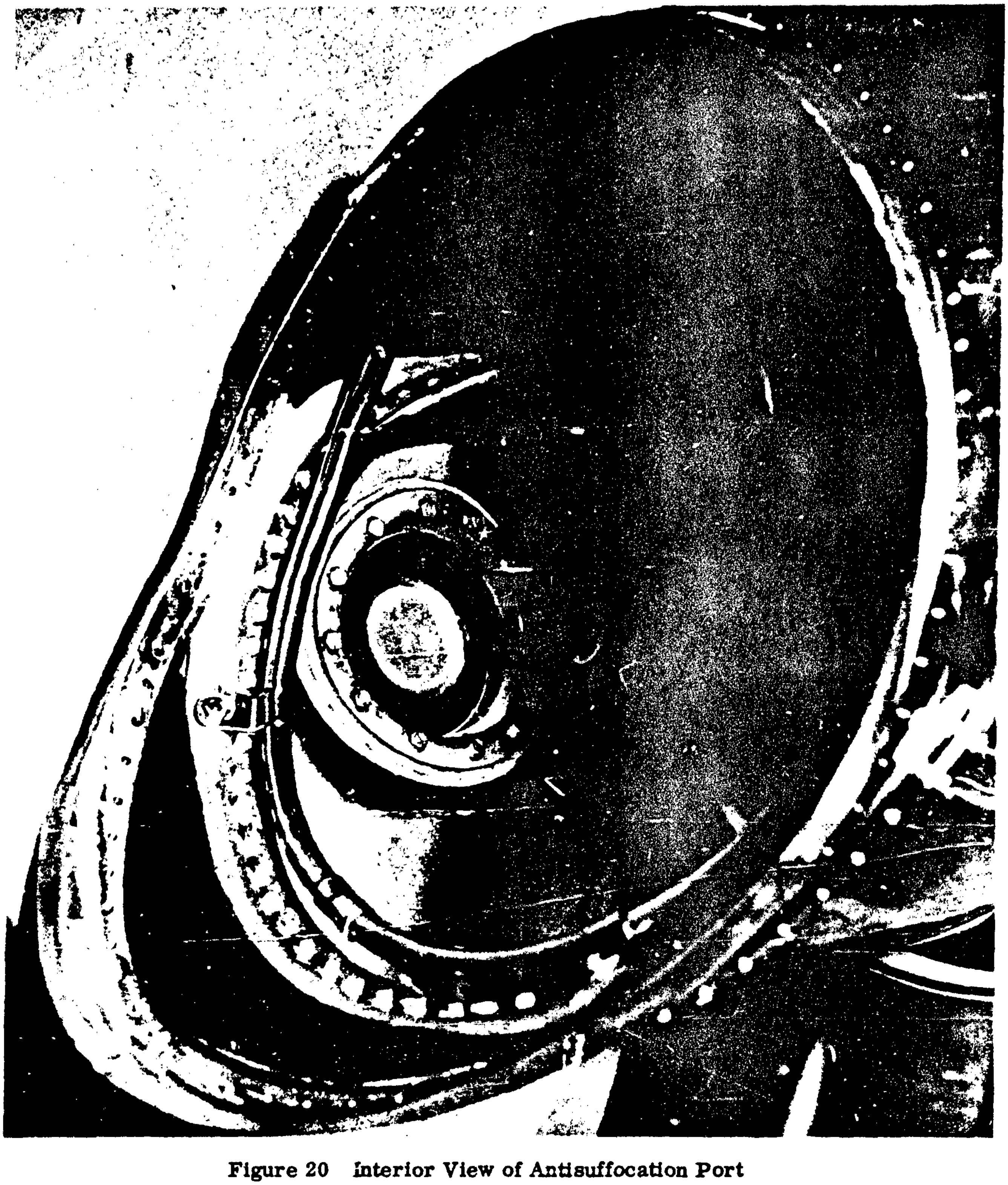


Figure 20 Interior View of Antisuffocation Port

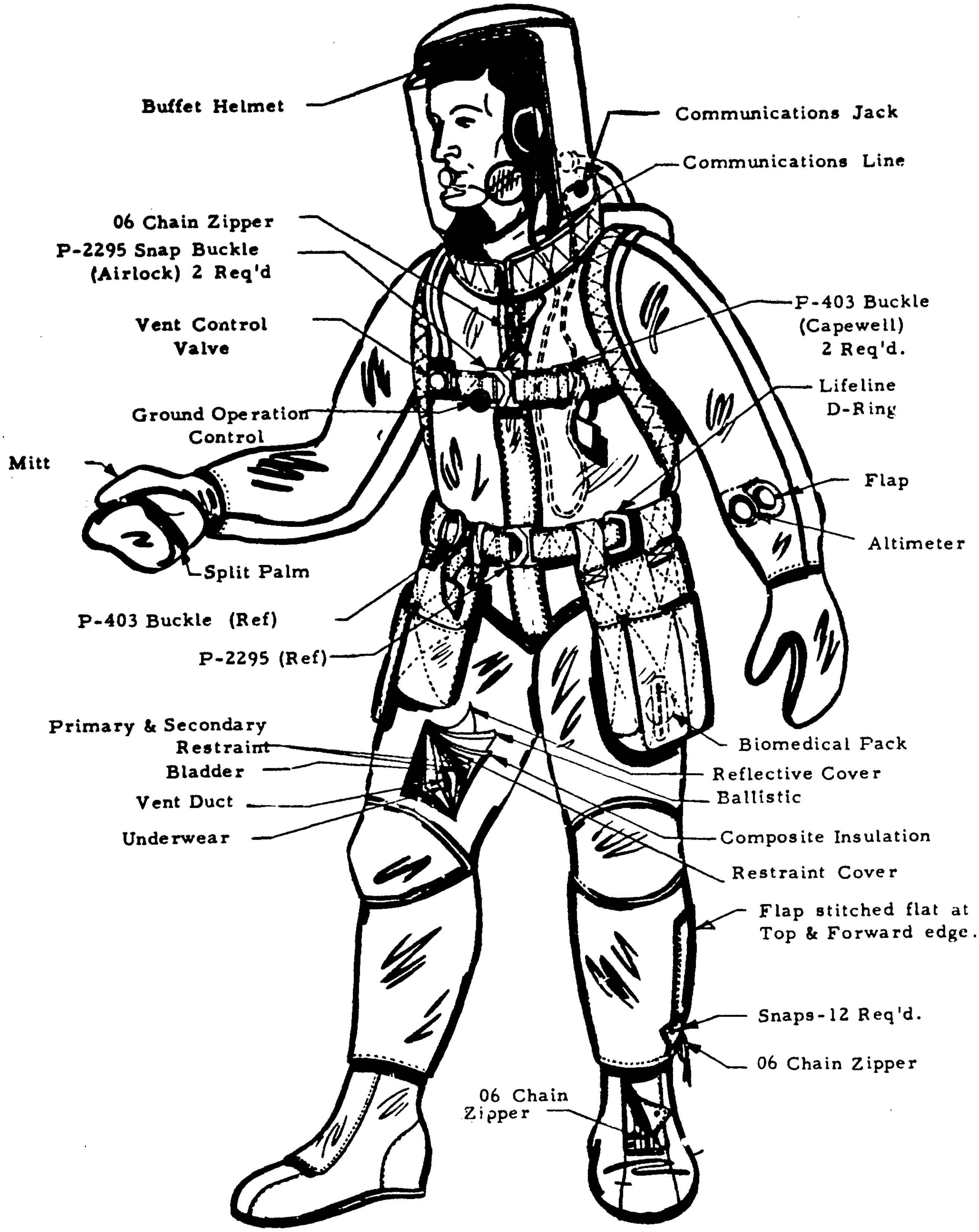


Figure 21. Exterior View of Final Configuration

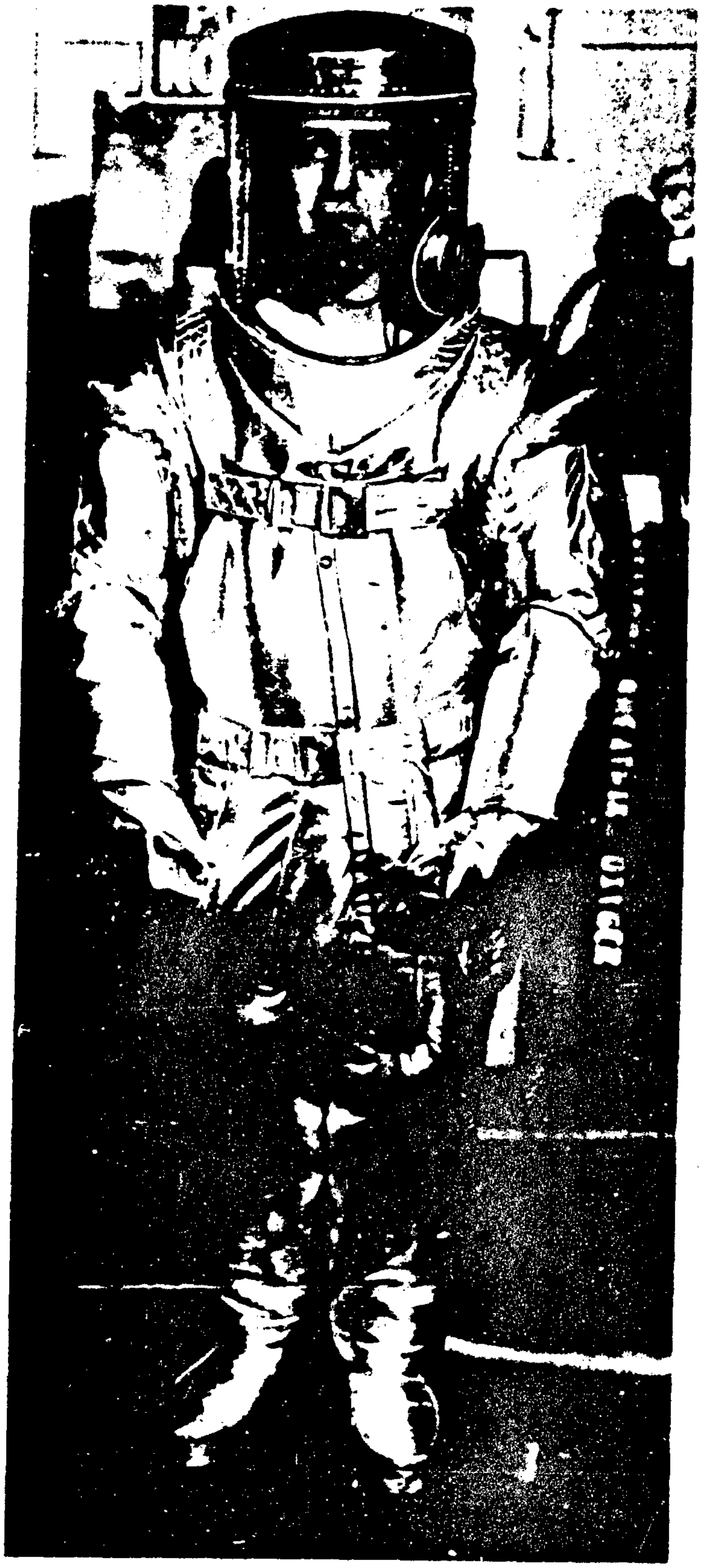


Figure 22. Front View of Completed Assembly

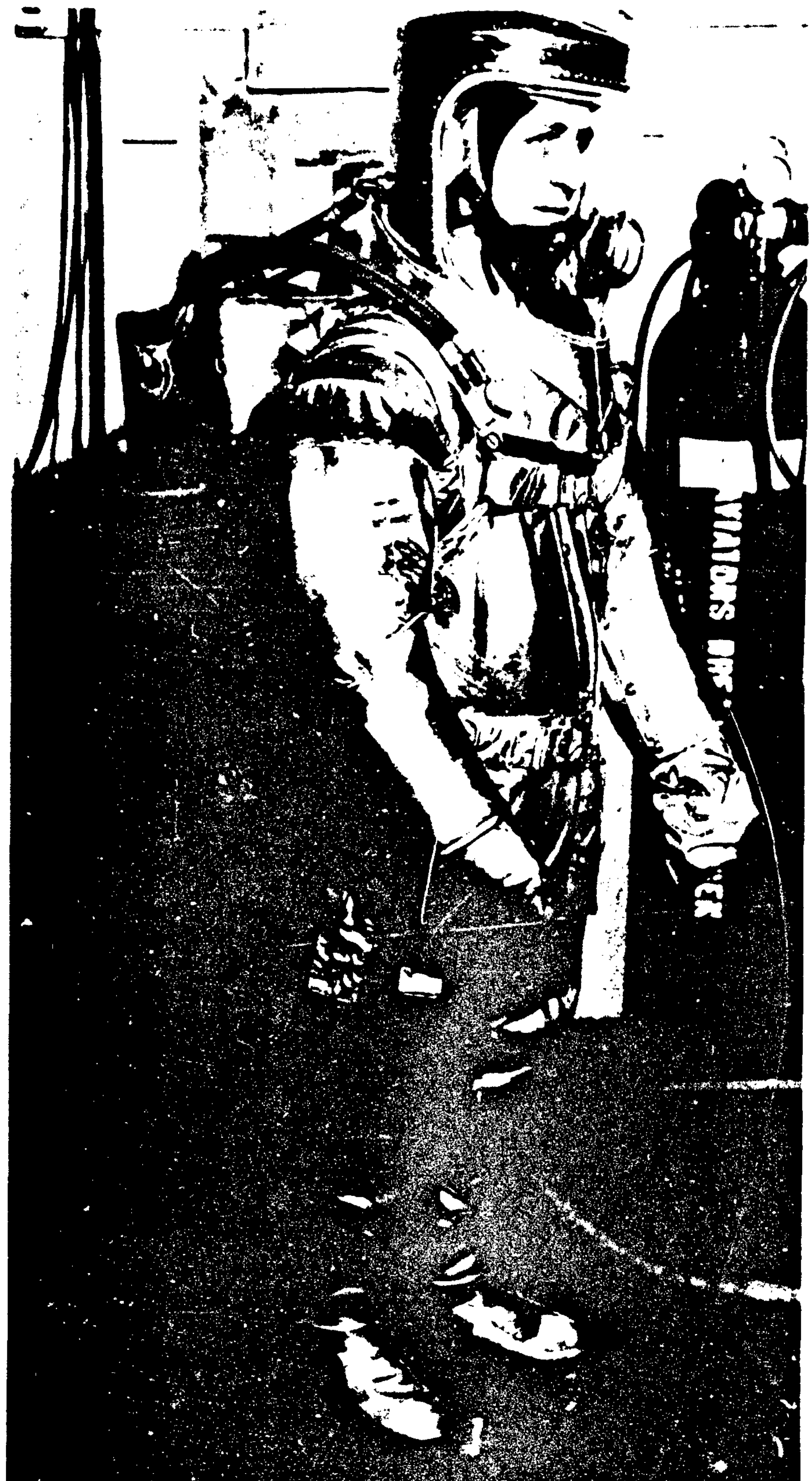


Figure 23. Side View of Completed Assembly

Liner - mercerized cotton
Vent Ducts - bladder cloth (nylon/rubber coated-P711) and springs
Gas container - TDA bladder cloth
Inner restraint - HT-1 fabric and cord
Restraint - HT-1, 32 lb test, line Link Net
Cover - mercerized cotton

c. Hardware Installed in the Torso

Altimeter (suit pressure shown in equivalent altitude in feet) ACS-1208 located on left forearm
Relief valve (6.0 psi) ASC-3880 located on left upper leg in the hip area
Biomedical pack (entry and plug) located on left upper leg
Inlet suit fitting, Air Lock P/N 785 located in the lower left shoulder blade area
Exhaust fitting Air Lock P/N 785 located in the lower right shoulder blade area

d. Outer Layer of Insulation/Shielding Package

Liner - mercerized cotton (blue)		
Insulation - Mylar - aluminized	8 layers	These materials
Leno No. 382	8 layers	are alternated.
Graphite fibers black	1 layer	
Leno No. 382	8 layers	These materials
Mylar aluminized	8 layers	are alternated.
Ballistic shielding - ballistic nylon felt (compressed to 1/8 in.)		
Outer cover - HT-1 fabric - aluminized		

A separate bladder cover or restraint boot, constructed of aluminized HT-1 with a Dynel® sole, is used to maintain pressure boot conformity and for ease of walking.

2. Torso Gas Container

a. Basic material - HT-1 braided cord, 32 lb test

Neck opening - 3/4 inch single-bead HT-1 webbing tape
Slide fasteners - Entry: 38-1/2 inch, backup nylon webbing 09 chain
Leg attaching - nylon webbing, 06 chain
Openings - Two in back torso for oxygen inlet and outlet, one in lower left arm for altimeter, one in upper left leg for biomedical pack

Altimeter opening - neoprene rubber molded ring with HT-1 attaching loop tape

Arms and legs takeup - HT-1 fabric, 2-ply with HT-1 attaching loop tapes and lacings

Wrist flange - molded-type neoprene rubber (for bearing disconnect)

Knots - braided cord - standard knots, singed and coated with Omni cement

Arms - flat patterned, one piece arm and elbow

Legs - flat patterned, one piece

All stitching is with HT-1 thread (size E)

HT-1 lacing cord

b. Ventilating Duct System

Duct material - bladder cloth

Springs, stainless steel, three to each arm, one to each side of top head, and four to each leg. Attached to liner by tabs at various locations. HT-1 thread (size E) used for stitching.

Foot vent - Tri-lok from midcalf to tips of toes - bottoms of feet. All stitching in the ventilation system itself is with sage green nylon thread.

c. Liner (inner)

Mercerized cotton (blue)

Banlon®, black - located at neck, midtorso axillary area

Holland® back taped located at the wrist, neck, biomedical pack entry, lower legs, and main entry slide closure for attaching to the gas container

Cotton strip, 1/4 in. wide for attaching Banlon in neck area to Holland back tape and mercerized cotton

All stitching is with HT-1 thread (size E).

d. Restraint Cover

Mercerized cotton (blue) - This layer was added to prevent snagging or hangup of the restraint if the assembly should be worn for evaluation purposes without the insulation and outer coverall unit. It is laced to the bottom of the takeup on arms, legs, and all openings.

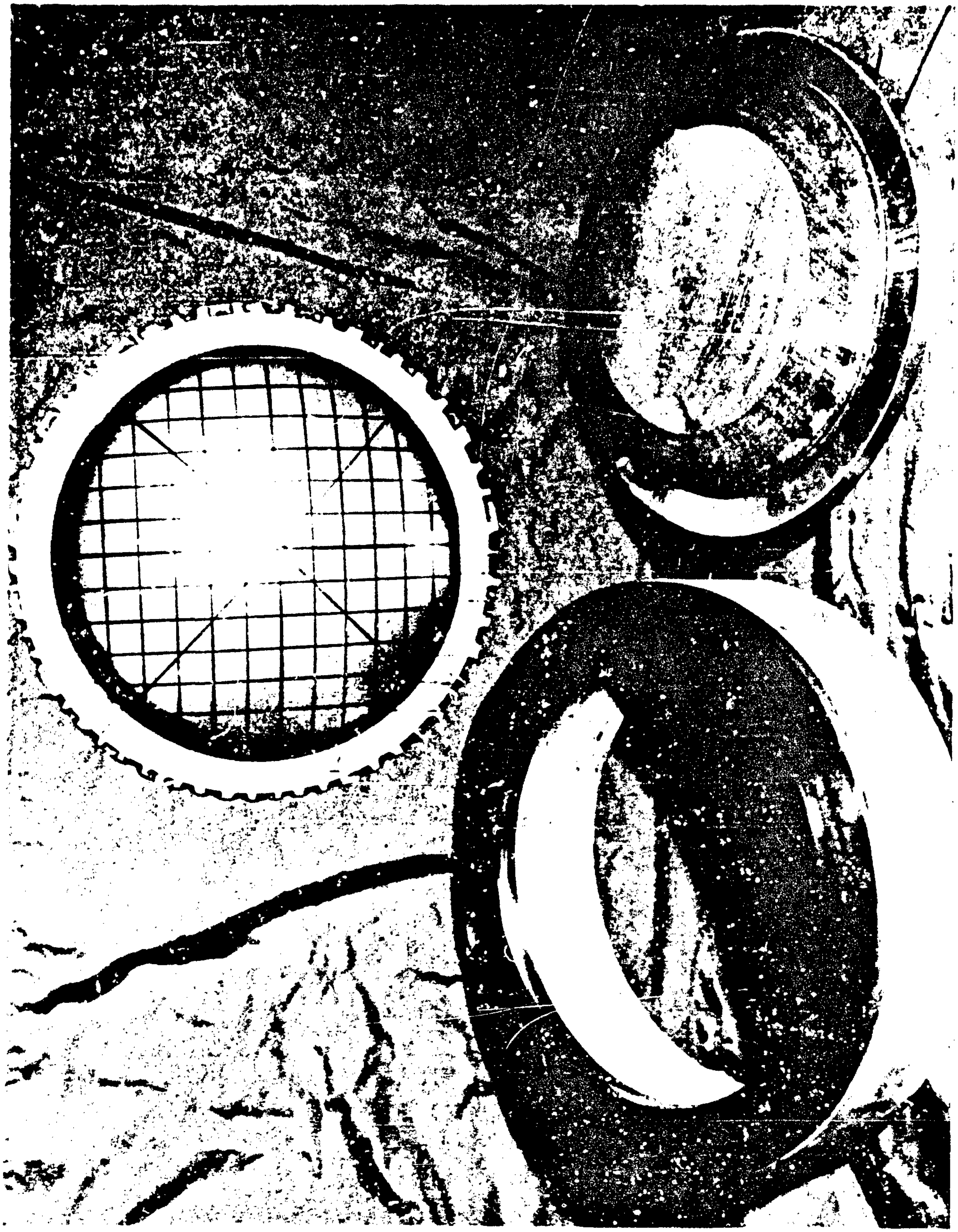
3. Helmet

a. Final Basic Dome Construction

Dome construction proceeded as outlined in the original proposal. The cylindrical shape was based on the sizing tariffs where applicable for helmet design as specified in WADC Technical Report 56-404 and WADD Technical Report 60-631.[13,14] The basic dome size was established, and a wooden full scale mockup was fabricated as a guide for construction of the finished item. The first approach to helmet fabrication was the employment of metal spinning techniques.

The wooden mandrels for spin forming were completed. The metal used in the dome was type I8-9LW stainless steel, 0.019 in. thick. Three attempts were made to fabricate the crown portion of the enclosure, but each effort failed because of metal fatigue and excessive thinning and wrinkling of the metal at the edges. The mandrel was modified, an aluminum female ring with wooden supports constructed, and the crown pressed hydraulically. After four attempts, with alterations between each effort, a satisfactory crown was fabricated (fig. 24). The crown dimensions were then checked, and, since all were within predetermined and accepted tolerances, the flash was trimmed and preliminary polishing completed. Many studies were made of seam construction and weldments to establish maximum strength, minimum weight, positive gas integrity, and appearance of the end item. The crown piece was spot welded in final position and the seams were then sealed using a hard silver solder (Airco sil-45, low temperature silver brazing alloy 1/32 in. Kwick Flux No. 54, silver brazing flux).

The removable lens frame, lens opening support, and hole spacing were established by test results of anticipated loadings and pressures during the early phase. The lens frame and outer support were fabricated in quarter pieces of No. 304 stainless steel, 1/8 in. thick and 7/16 in. wide, and spot welded to the dome. Butt joints were silver brazed. The inner clamping frame (lens) was fashioned of quarter pieces of No. 304 stainless steel, 1/32 in. thick and 7/8 in. wide, welded, and the outer edge rolled to capture lens and gasket sealing compounds for maximum sealing (fig. 25). Hole alignment and drilling were completed using results from earlier test evaluations (fig. 26). This liner was constructed of six layers of materials which were specially selected for their insulation qualities. These materials in the order of their proximity to the subject are:



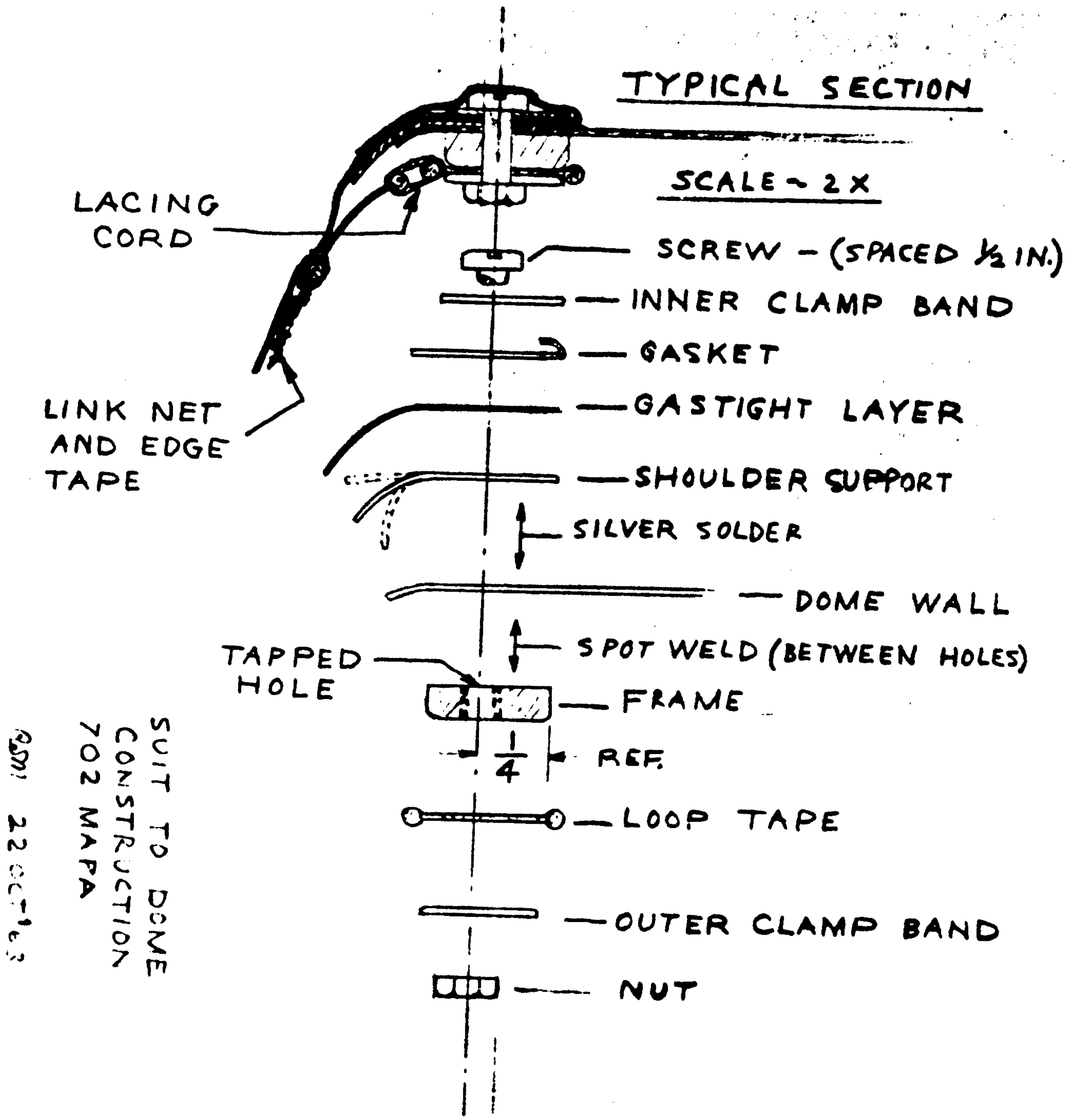


Figure 25. Suit to Dome Attachment

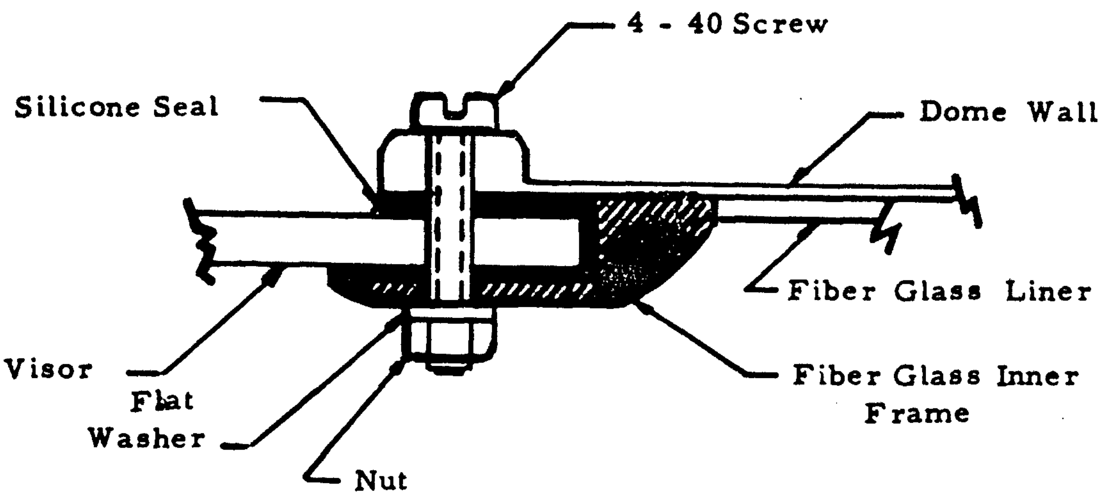


Figure 26. Typical Cross Section of Visor Seam

Cabretta leather
Vinyl foam, 1/16 in. thick
Urethane foam, 1/4 in. thick (compressed)
Aluminum asbestos (aluminum side toward subject)
Graphite fibers
Aluminized HT-1 (aluminum side toward helmet)

This insulation liner is attached to the dome wall interior with strips of Velcro® fastener fabric to facilitate easy removal or replacement (figs. 27, 28, 29).

The suit-to-dome attachment ring was designed, flat patterns made, and the ring fabricated in a manner similar to that described above. Since presently used full pressure helmets (domes) are basically oval shaped, which is a tested and proven principle, the problem of overpressure and deformation of this head enclosure concerned many people. The results of helmet testing are set forth in Appendix II.

Some buffeting protection is provided by a 1 by 1/2 in. foam band contained within a separate 100% nylon stretch fabric encircling the critical areas of the head. This inner helmet is so constructed as to permit maximum stretch to fit a number of head sizes.

The inner helmet is equipped with two small plastic earcups (fig. 30) designed and molded by the David Clark Company. The sealing edges are covered with a David Clark Company developed ear seal of urethane rubber copolymer to provide comfort and noise-free communications. Each earcup is equipped with a Dyna-Magnetic® 19-ohm receiver, type 265-B-120, connected to a personal lead by a U-173/U male, two pronged plug. These, in turn, mate with a U-172/U female socket. The personal lead connector is a miniature Viking receptacle, VR7/4AB13, which mates with the Viking plug, V-7/4CE6 (also miniature).

The chin cup mounted Roanwel M-101/A1C microphone remains in a position relative to the lips to assure maximum speech pickup at all times.

4. Hand Covering

a. Gloves

Three pairs of gloves, sized E, H, and K, in accordance with WADC-TR-56-599[12] were connectable to the assembly by an

Figure 27. Left Back Inner View of Dome Liner Installation with Velcro

Figure 28. Right Back Inner View of Dome Liner Installation with Velcro

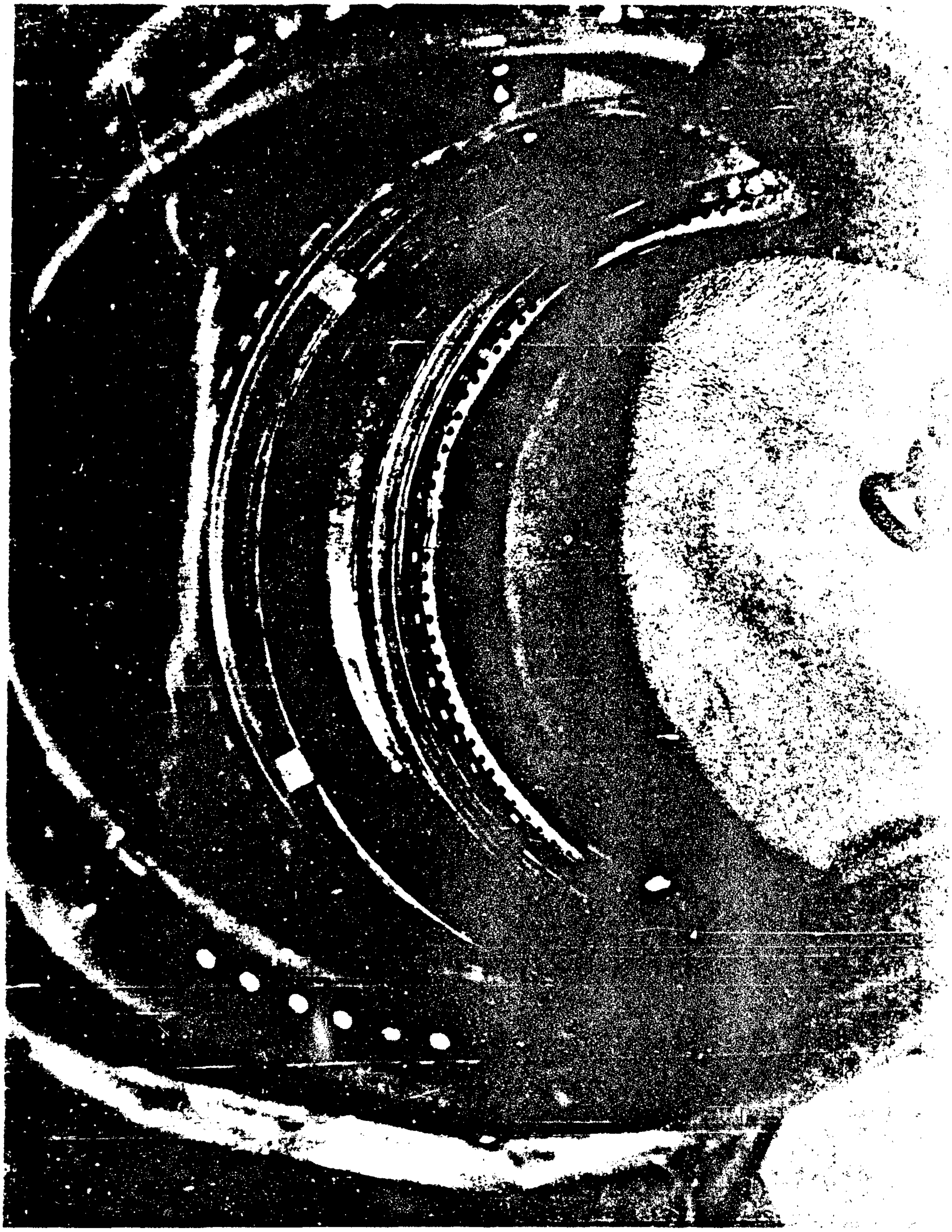


Figure 29. Front Inner View of Dome Liner Installation with Velcro

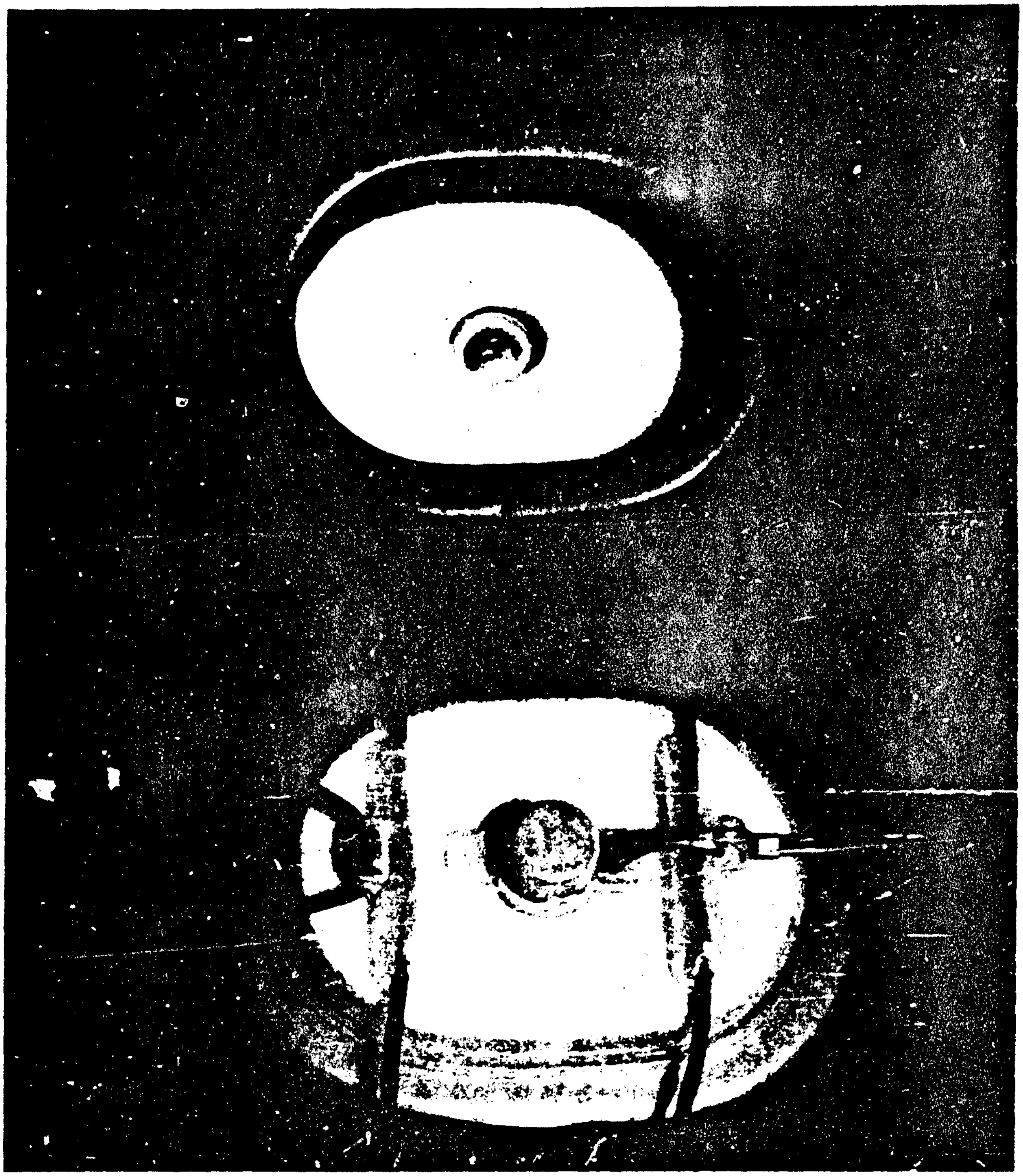


Figure 30. Plastic Earcups with Miniature Receivers

Air Lock Inc wrist disconnect P/N AL-715. The bladder is HT-1 fabric, Omni coated. The restraint portion is of HT-1 line and has been eliminated from the backs of the fingers. Aluminized HT-1 fabric is used for the outer glove with uncoated HT-1 fabric in the palms. The complete glove is attached to the wrist disconnect with special molded neoprene flanges.

b. Mitts

The insulation package was eliminated from the gloves to allow maximum dexterity of the gloved hand. To compensate for space environment problems, an overmitt was designed and fabricated in two sizes. The composite is an inner HT-1 fabric, an insulation package, and an outer aluminized HT-1. An 09 chain fastener with a snapclosed flap was installed on the mitt (ulnar side) to permit the hand to project outside for dexterity purposes. The mitt is a slip-on type and not attached to the suit.

5. Boots

a. Inner Boot (cover over gas container)

HT-1 fabric, aluminum coated (outside layer)
Sole - 2 ply Dynel covered with HT-1 fabric
Entry slide fastener - rear of boot, 09 chain, nylon webbing
Attaching slide fastener - top, circumference, 09 chain nylon webbing
All stitching is with HT-1 thread (size E).

b. Outer Boot (from inside to outer cover)

Mercerized cotton - blue		
Mylar aluminized	8 layers	These two materials
Leno	8 layers	are alternated.
Ballistic felt - 1/8 in. thick		
Mercerized cotton - blue		
HT-1 fabric, aluminized		
Sole - molded Omni 1/8 in. thick		
Entry slide fastener - rear of boot - 06 chain on HT-1 webbing		
Slide fastener protective flap - constructed of same material as outer boot. Composite has been halved and overlaps so that, when it is closed, complete protection is provided. Three nickel plated snap fasteners secure the flap. All stitching is with HT-1 thread (size E).		

6. Outer Coverall

Aluminized HT-1 fabric was sewed to the insulation package. The cuffs of the sleeves and legs are loose fitting, tapered, and have chain slide fasteners with protective covers. The sleeve cuffs extend 3 in. below the wrist disconnects. The center front opening is an 06 chain slide fastener. All fasteners have snapclosed overflaps (fig. 21).

7. Accessories

a. Backpack Harness

The harness to support the backpack is made of 2-ply aluminized HT-1 fabric. To provide strength and for reinforcement, it is stitched to a final width of 1-3/4 in. and is approximately 3/16 in. thick.

b. Life Line Attachment and Tool Apron

The waist type safety belt of material with standard 3/4 in. parachute "D" rings is located on the left and right front waist. A tool apron of aluminized HT-1 fabric folded and stitched with pockets is attached to the safety belt and located to the left and right of center front waist. An adjustable positive-locking military-type buckle is located center front.

SECTION V

DISCUSSION AND CONCLUSIONS

A. Upon completion of this program, the suit assembly consisted of the following major components:

1. Permanently attached stainless steel dome with a sealed lens, communications system, insulation package, antibuffet protection, ventilation and lens antifog system, and an antiglare shield.

2. Omnicoated gas container with inlet-outlet fittings, biomedical data fitting, over-pressure relief valve, detachable gloves, ventilation duct system, and a pressure gage.

3. Restraint layer constructed of a Link Net material fabricated of HT-1 fabric.

4. Cover layer constructed of aluminized HT-1 material.

5. Coverall to provide protection against hypervelocity projectiles (micrometeorites), solar radiation, and temperature extremes.

6. Liner

7. Undergarment

8. Outer Boots

9. Gloves

HT-1 fabric, thread, and lacing cord have been tested, and known reactions of these materials in a vacuum and high temperatures indicated their value in an assembly of this type.

Omni fabric and compound has a proven capability of withstanding operational use in repeated exposures to 400F, pressures of 10^{-5} mm Hg, and inert gases (argon).

Ballistic felt (compressed) was used to provide some protection against hypervelocity projectiles. Although this felt did not provide 100% protection, it was an advancement over the materials used in existing pressure suit assemblies.

Insulation in the form of multilayers of Leno and aluminized Mylar was an approach which laboratory tests proved to be efficient and lightweight.

SECTION VI

RECOMMENDATIONS FOR FURTHER RESEARCH AND DEVELOPMENT

The following areas are recommended for further research and development:

1. Improve insulation quality by further investigation of materials.
2. Obtain a safety-glass type visor with adequate heating methods for defogging purposes.
3. Develop a two-way communication system for space operation.
4. Establish a pneumatic antibuffeting pad system within the dome to provide additional head protection.
5. Control thermal conditions within the dome through use of circulating fluids.
6. Investigate lightweight panels for the assembly's exterior layer for use as protection against hypervelocity projectiles.
7. Develop a positive closing pressure seal.
8. Improve locking mechanism on iniet/outlet vent fittings.
9. Improve mobility in all joint areas.
10. Improve the ventilation system.
11. Improve finger dexterity and mobility in the gloves.

APPENDIX I

PROTECTIVE SUIT ASSEMBLY ENVIRONMENTAL CONTROL SYSTEM

The environmental control system as originally proposed was a semi-open, recirculating system powered by the gasification of liquid oxygen and dumping of gas into a vacuum. The design objective for the capacity of the system was 4 hours of operation at 5 psia. The system included an oxygen tank, a heat exchanger, the turbine-compressor, and injector with suitable safety valves and controls. The principal differentiating feature of this system was the turbine-compressor and injector arrangement. Theoretically the suit vent gas is forced through the suit by an injector powered by the expansion and gas conversion of liquid oxygen and by the turbine-compressor, the turbine being powered by bleed-off of gases to a vacuum environment.

The design provided for 5 psig pressure operation at ground level or at altitude, with emphasis on effective ground level operation. The preliminary design was reevaluated and modified to provide this requirement. The components of the system were fabricated and tested in a laboratory test setup (fig. 31) with the suited man being simulated by a load of 500 Btu/hr with a saturated gas flow and a suit back pressure of 5 inches of water. Figure 32 illustrates the data obtained in a simulated 4-hour run in a vacuum environment using this test setup. Figure 33, which shows oxygen consumption as a function of return flow to the system, indicates that in this system the best ratio of return flow to fresh oxygen flow is approximately 4 to 1. Suitable flows could not be obtained at ground level.

The components were assembled and the complete unit with its protective cover delivered to AMRL. In the demonstration run at the time of delivery, the unit would not function. The unit was disassembled and the turbine-compressor examined. The compressor fan and blade had seized or frozen to the housing and would not turn. This design concept was then dropped and the system modified to use only an injector (fig. 34). The modified unit, when started with a full tank, operates for 70 min at full flow of 220 lpm against a suit back pressure of 5 in. of water.

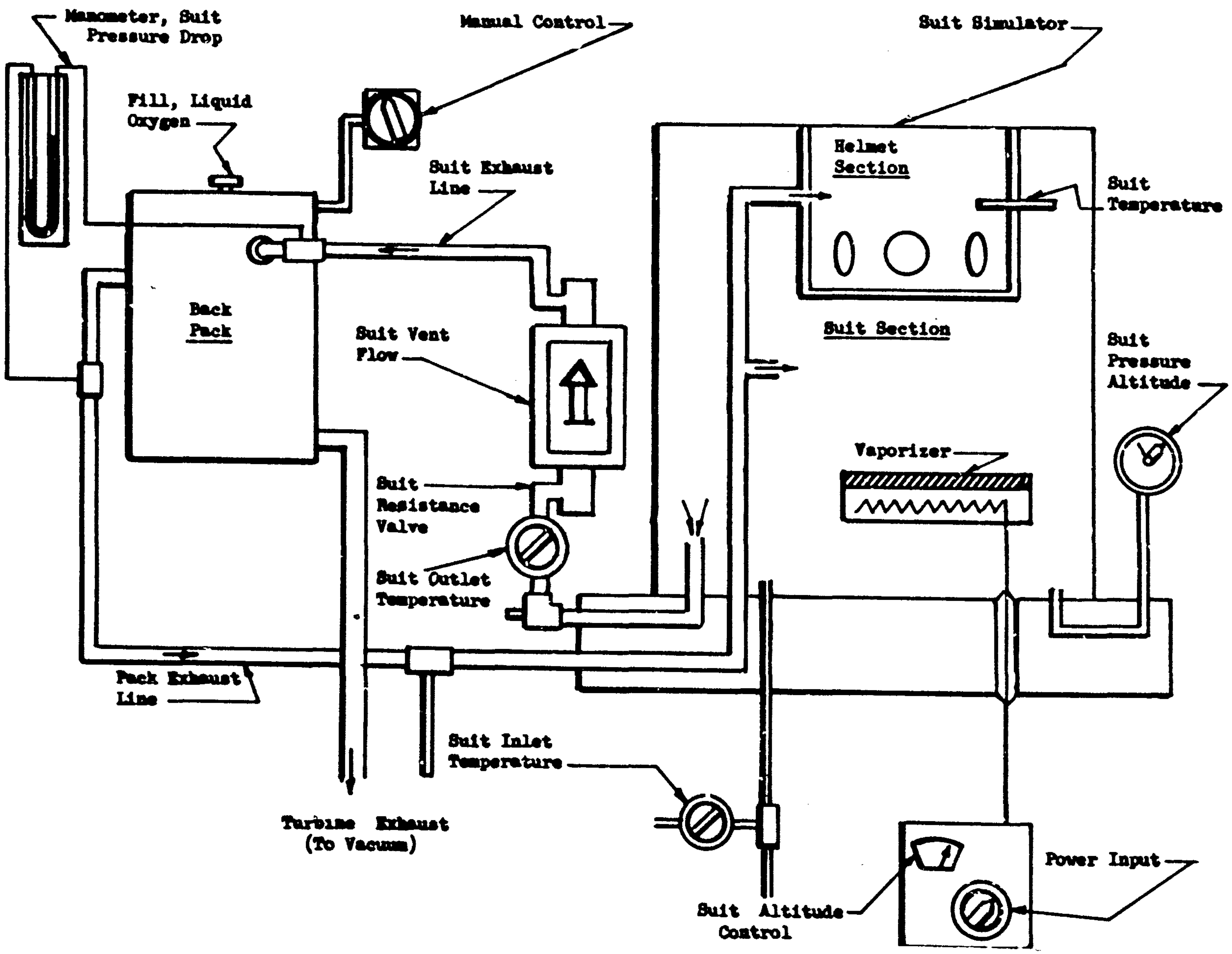


Figure 31. Control System Test Setup

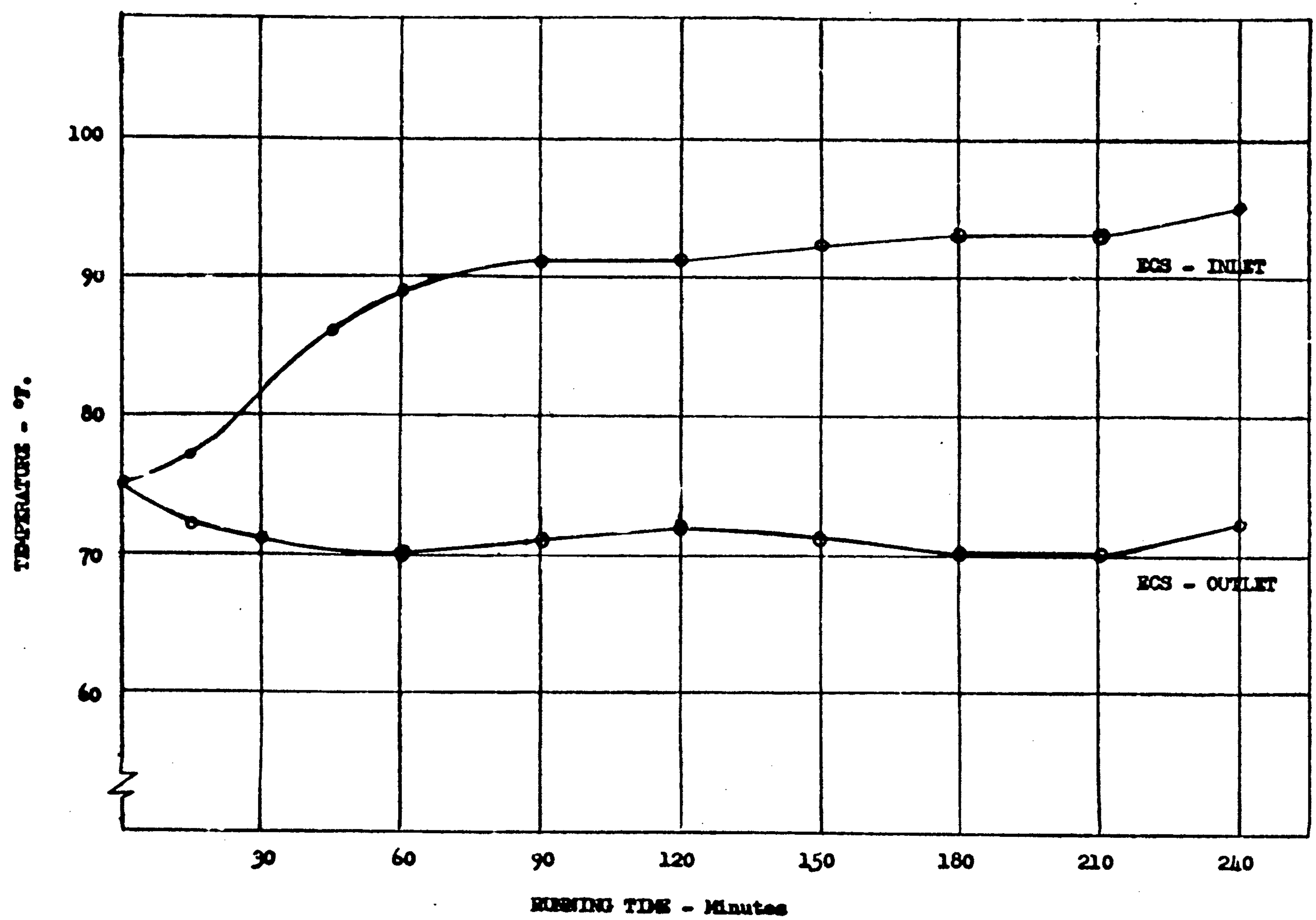


Figure 32. Environmental Control System Cooling Performance

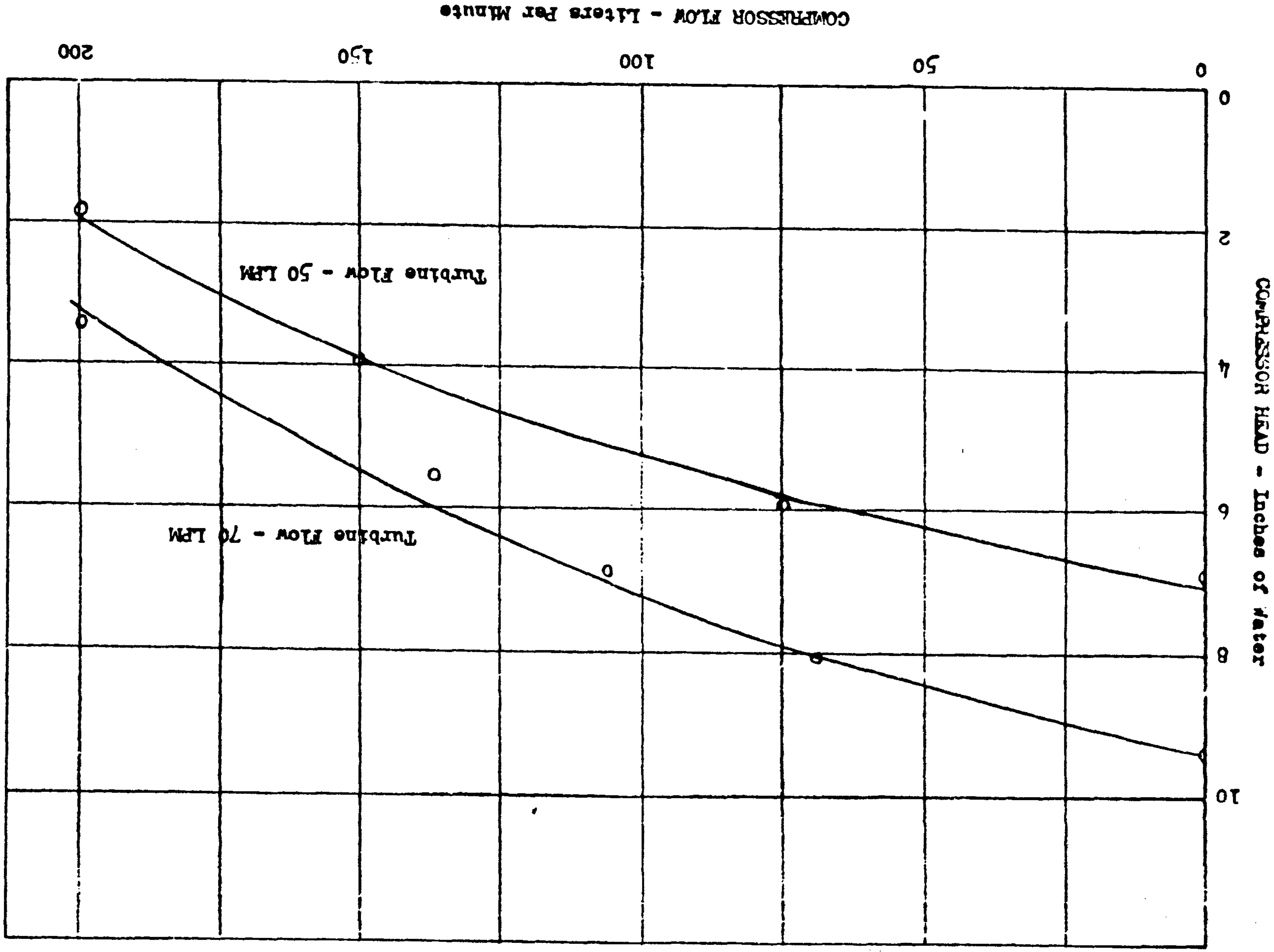
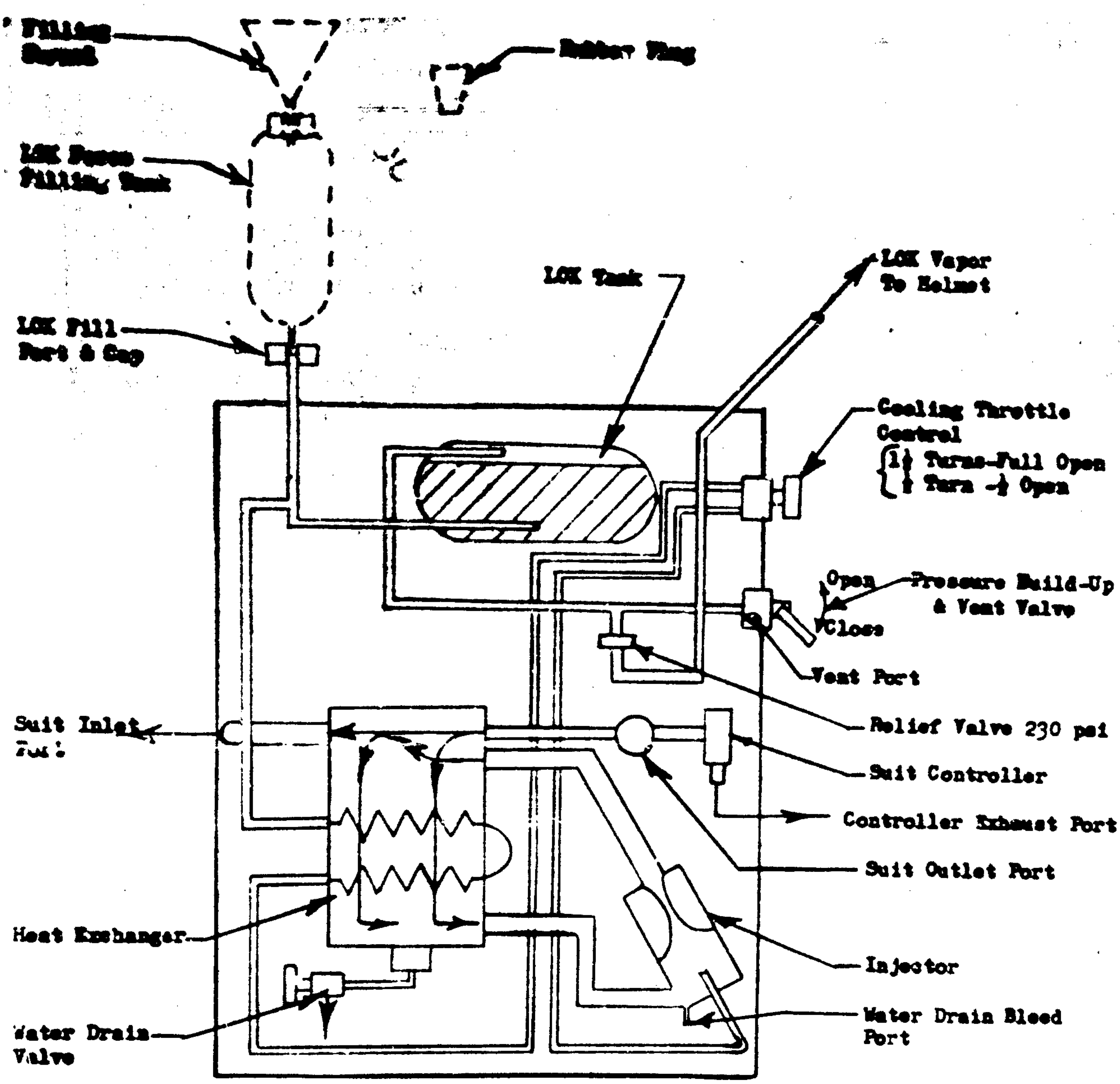


Figure 33. Turbo-Compressor Performance at 27,000 Feet



FILLING PROCEDURE

1. Open PB&V Valve
2. Attach Force Fill Tank To Fill Port
3. Put Funnel full of LOX into Fill Tank; Vent Top of Fill Tank
4. Force LOX into LOX Tank With Plug
5. Repeat until liquid comes from PB&V Valve
6. Remove FF Tank, use Caution due to Splash back from fill line or Excess LOX in FF Tank
7. Attach LOX Fill Cap
8. Close PB&V Valve
9. With Cooling Throttle Control Closed Allow 10 min Pressure Build-up Before Opening

PERFORMANCE:

A full tank yields 70 minutes at full vent flow of 220 LPM (Appx. 7.5 CFM) and 5 inches of water suit pressure drop. Flow at altitudes above 26,000 Ft., 280 actual LPM. Suit pressure altitude - 26,000 Ft. Cooling Capacity - 820 BTU/Hr.

Figure 34. Environmental Spacesuit Control System

APPENDIX II

DOME TEST RESULTS

The following tests were conducted on the dome before its attachment to the suit:

A. Structural Pressure Test

The overpressure testing of the helmet was conducted by constructing a fabric cap capable of retaining the maximum test pressures and attaching this cap to the lower section of the dome. The liquid oxygen input line was used to pressurize the dome. A special fitting was attached to the communication entry port to accept a gage used for pressure readings.

1. Equipment

   a. Dome with bladder installed in neck opening
   b. Pressure gage (0 to 15 psi)
   c. Adjustable air supply

2. Test Setup

   Refer to fig. 35.

3. Test Procedure

   a. Connect dome to air supply.
   b. Mount dome, with bladder at top, to bench for safety reasons.
   c. Gradually inflate dome to 12 psig and hold for 30 minutes.
   d. Record damage, location of leaks, and any other indications of failure.

4. Test Results

   There was no evidence of structural damage or leakage of the assembled dome. Minor leaks were detected around the temporary bladder which has no connection with the dome except for test purposes.

5. Conclusions

   The dome will withstand 12 psig for 30 min. without damage.

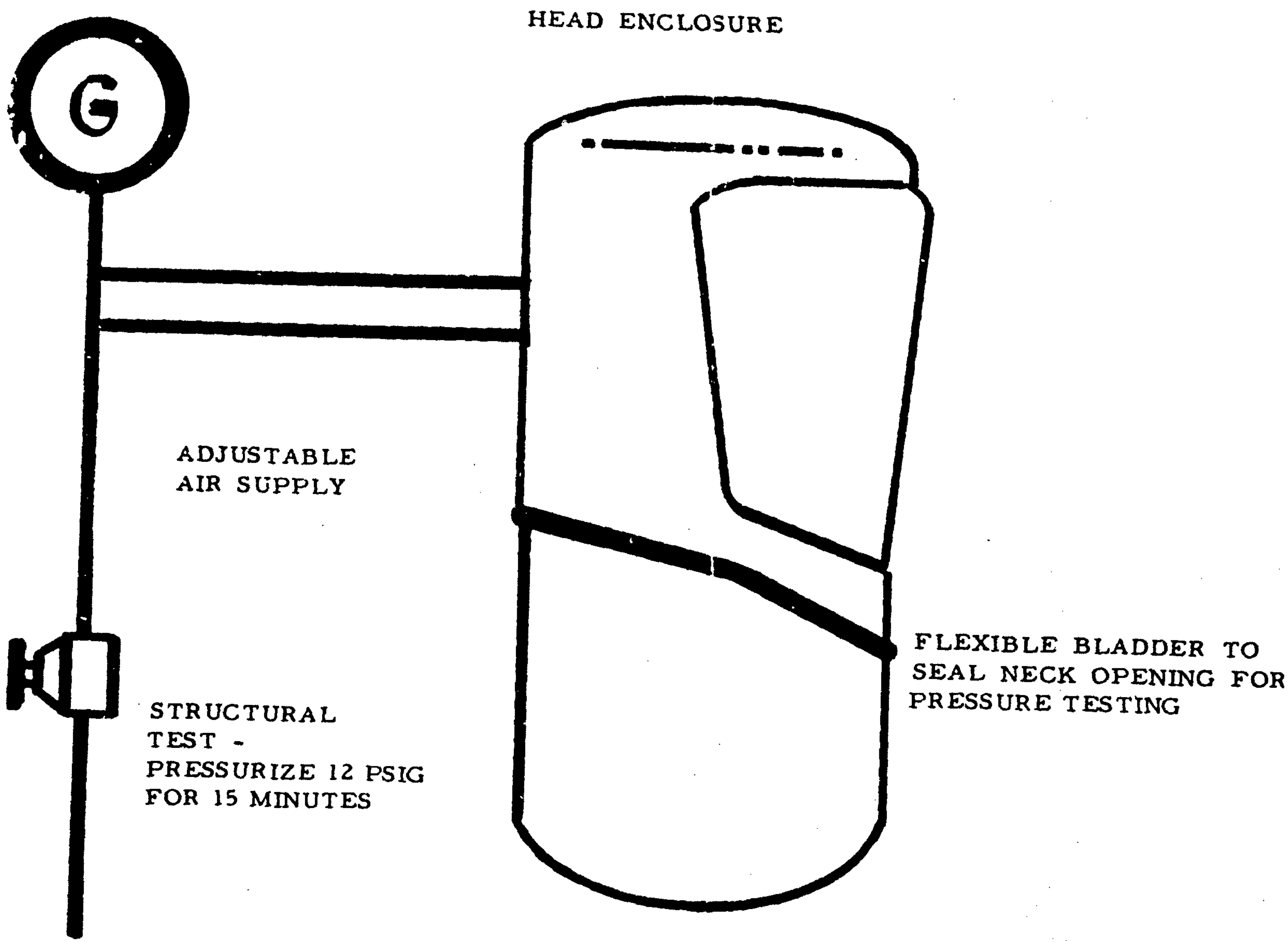


Figure 35. Dome Pressure Test Setup

B. Leak Test (Visor, Fittings, and Seams)

Leak testing of the helmet was conducted to determine the effectiveness of the sealing method used on the fittings and visor as installed in the dome.

1. Equipment

a. Dome with bladder installed in neck opening
b. Leak test solution
c. Bristle brush
d. Adjustable air supply

2. Test Setup

Refer to fig. 35.

3. Test Procedure

a. Connect dome to air supply.
b. Gradually inflate dome to 5 psig and hold for 30 min.
c. Check all seams, fittings, screws, bolts, and other possible leak points with an approved gas leak detector solution (not soap). Application is by the bristle brush method. Leakage is determined by appearance of any bubbles in the solution.

4. Test Results

The visor sealing seam, communication entry, and oxygen inlet fittings were all determined to have zero leakage.

5. Conclusions

The sealing methods used in this application prevent gas leakage at 5 psig for 30 min.

C. Spray Bar Back-Pressure Test

Spray bar back-pressure testing was conducted to establish the amount of back pressure caused by the defogging spray bar.

1. Equipment

a. Spray bar as used in this dome
b. Testing manifold
c. Pressure gage
d. Flow meter
e. Adjustable air supply

2. **Test Setup**

Refer to fig. 36.

3. **Test Comments**

With ends A and B open to ambient conditions, a reading of 0.8 in. water on the water manometer was obtained at a flow of 122 lpm. The following assumption was considered valid for this test: Zero back pressure would exist if 0.8 inches of water and 122-liters flow could be measured with the spray bar connected as shown in fig. 36. The back pressure of the spray bar is equal to measured pressure minus 0.8 inches of water (the loss known to exist at manifold).

4. **Test Procedure**

a. Conduct back pressure check of test equipment to determine rate of flow before spray bar check.
b. Connect spray bar to air supply.
c. Conduct back pressure check of spray bar using same rate of flow as for the test equipment check in (1) above.
d. Record back pressure reading through several increases in rate of flow.

5. **Test Results**

Refer to Table I.

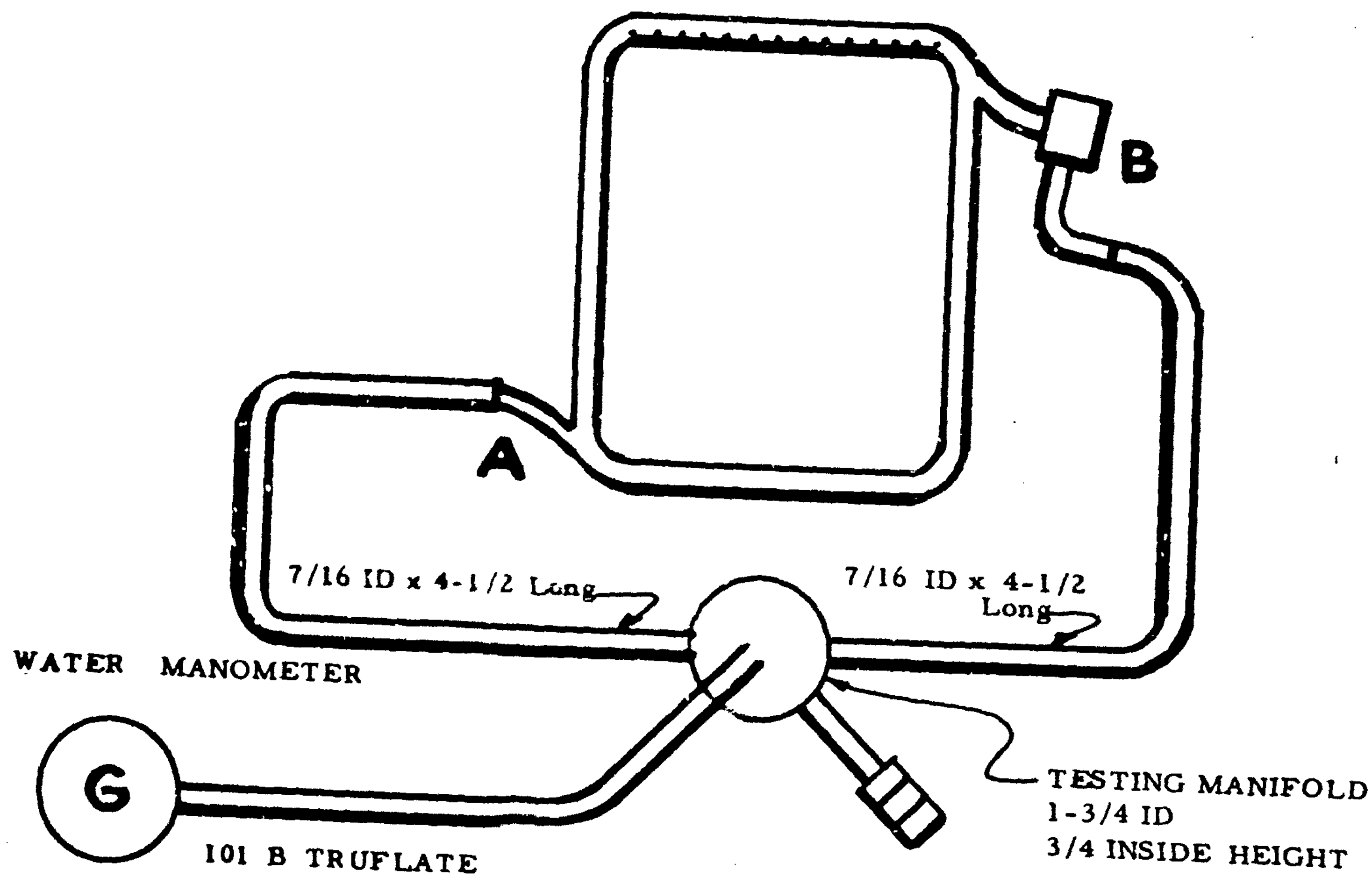


Figure 36. Spray Bar Back Pressure Test Setup

Table I

SPRAY BAR FLOW TEST

Manifold Pressure H_2O	Flow Reading Liters/Min.	Pressure @ Flow Meter PSIG	Pressure Correction Factor	Corrected Flow Liters/Min.	Corrected Flow Cubic Ft.	Spray Bar Back Pressure A-8
1	70	1	1.02	71.4	2.5	.2
2	98	2.25	1.08	105.8	3.7	1.2
3	120	3.5	1.1	132.	4.7	2.2
4	134	4.25	1.12	150.	5.3	3.2
5	146	5.5	1.18	172.	6.	4.2
6	156	6.5	1.2	187.	6.6	5.2

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Security Classification

DOCUMENT CONTROL DATA - R&D	
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)	
1. ORIGINATING ACTIVITY (Corporate author) David Clark Company, Inc. Worcester Mass. 01604, Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A
3. REPORT TITLE RESEARCH & DEVELOPMENT OF EXTRAVEHICULAR PROTECTIVE ASSEMBLY	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report 2 July 1962 - 30 April 1964	
5. AUTHOR(S) (Last name, first name, initial) Osborne, Norman H.; Rock, Lee C.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
October 1966	64	14

8a. CONTRACT OR GRANT NO. AF 33(657)-9532 b. PROJECT NO. 6301 c. Task no. 630104 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AMRL-TR-66-143
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Aerospace Medical Research Laboratories Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, Ohio

13. ABSTRACT

A prototype extravehicular pressure suit assembly was designed and fabricated for use in earth and lunar environments. Conditions of space environment, preliminary design concepts, laboratory evaluations of materials, the intermediate model configuration, and the final suit assembly are described in detail. This assembly consists of special underwear, liner, ventilation system, gas container, restraint layer and cover, insulation, micrometeorite protection, an outer reflective layer, and a life support system. The life support system is a liquid oxygen, semi-closed, recirculating-type backpack. The use of new material distinguishes this assembly from current pressure suits. Recommendations for further research and development are included.

DD FORM 1 JAN 64 1473

Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Extravehicular protective assembly materials Space personal protective garments Environmental isolation Pressure suits Dual restraint layers for mobility Link net restraint (HT-1)						

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