GARRETT

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
9851-9951 SEPULVEDA BLVD. • LOS ANGELES, CALIFORNIA 90009
TELEPHONE: SPRING 6-1010, ORCHARD 0-0161 • CABLE: GARRETTAIR LOS ANGELES

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AIRESEARCH MANUFACTURING COMPANY

Los Angeles, California

FINAL REPORT ON THE
INTRAVEHICULAR ACTIVITY SPACE SUIT
BY
AIRESEARCH MANUFACTURING COMPANY
FOR
NASA-MSC
CONTRACT NAS 9-7555

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Prepared by D. Friedman

Approved by W. Elkin
W. Elkin; IVA Suit
Program Chief Engineer

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1. INTRODUCTION

This report presents the results, conclusions and recommendations of the development effort performed by AiResearch Manufacturing Company, Los Angeles, California on the Intravehicular Activity (IVA) space suit program from 5 August 1968 to 1 February 1970 for NASA MSC under contract NAS 9-7555.

The program required design, development, fabrication and test of 2 prototype intravehicular space suit assemblies as part of a 4 phase program to develop and prove feasibility of an emergency protective suit with a design and operational integrity compatible with launch, vehicle transfer, reentry, pressurized and unpressurized cabin operations and other similar critical space flight activities.

1.1 SUIT FUNCTION

The primary function of the IVA suit is to protect the wearer from the effects of an evacuated cabin, thus providing sufficient body counterpressure, breathing oxygen and permitting respiratory balance between the nasal and torso areas. The IVA suit concept ensures that equal pressures are provided over the entire body and nasal area, such that normal breathing can be maintained without the use of a complicated breathing regulator or for that matter any type of breathing regulator. Mechanical pressure to the body is provided by an actively pressurized bladder system which covers 100 percent of the body when pressurized. A full pressure helmet is provided for the head and neck area.

Equal pressures are maintained by provided pressure to both helmet and torso simultaneously from the same source and by providing free interchange of gas between the two areas during breathing cycles. The bladders, arranged and manifolded to form a full suit, are restrained externally by an outer restraint garment which also acts as a protective insulator for the wearer. The bladders are prevented from irritating the wearers skin by an inner comfort liner which also aids in ease of donning. The three layers, the comfort liner, bladder suit and outer restraint garment are attached together to form a three layered flight suit which is donned as one piece, similar to a conventional flight suit. Auxiliary equipment provided to complete the suit assembly are a helmet support and neck seal cape, helmet, modified Air Force MG-1 partial pressure flying gloves, Gemini G-4C boots and Air-lock (Gemini-type) gas connectors for the flight suit and cape assembly. A liquid coolant vest as test support hardware is also provided for body cooling during the pressurized modes of operation. Normal operation requires that only the flight suit and boots be worn in a 5 psia cabin environment. The design goals were to provide a flight suit which could be worn as a constant wear garment as comfortable as normal flight clothing and which required no cooling provisions other than normal

convective/evaporative cooling. The flight suit was to be capable of continuous donning and doffing for periods up to one year, and was to have the capability of unaided donning within a two-minute period.

The pressurized mode of operation of the suit required that the remainder of the assembly other than flight suit could be completely donned and pressurized to 3.5 psig within a thirty second time period. The suit was to provide sufficient counterpressure against the torso area of the body such that pressure breathing would not result with the nasal pressure at 5.0 psia mixed gas or 3.5 psia oxygen pressure. The suit in the pressurized mode of operation was to provide sufficient mobility such that emergency crew operations could be performed for periods up to 8 hours.

1.2 PROGRAM GOALS

The IVA suit program goals were divided into a 4 phase effort as follows

Phase A--Consisted of a detailed design and configuration analysis of the proposed suit assembly, including prototype testing. The analysis took into consideration the materials, design concepts, components, construction and tests utilized with respect to the operational environments. A literature search and documentation of pressurization systems and the physiological effects of reduced atmospheric pressure relative to incomplete body pressures was also conducted and documented (see Appendix A).

Phase B--Consisted of the fabrication of one prototype suit assembly, based on the design analysis of Phase A. The prototype development and testing effort was also continued through Phase B.

Phase C--Consisted of verification testing of the Phase B prototype suit assembly by AiResearch personnel. Testing was conducted to pressures of 3.5 psi above ambient pressure.

Phase D--Consisted of the fabrication and test to 3.7 psid of one end-item suit assembly, based on the prototype design effort of Phase B and incorporating changes resulting from the Phase C effort. Prototype development effort was continued through Phase D with the incorporation of ideas into the Phase D suit assembly.

This report covers in depth the pertinent results of testing performed on both the Phase B and Phase D prototype suits, in addition to; (1) a description of the design of the IVA suit assembly; (2) fabrication techniques and problems encountered, and (3) recommendations for future development of the IVA suit concept. A summary, Section 2, presents highlights and the important aspects of the program and design goals achieved during the conduct of the 18 month program.

2. PROGRAM SUMMARY

2.1 INTRODUCTION

The Intravehicular Activity (IVA) suit program conducted at AiResearch, under NASA Contract NAS 9-7555, demonstrated that a constant wear type emergency garment could be worn as normal flight clothing. In case of a sudden cabin decompression the IVA suit assembly provides adequate body counter- and breathing oxygen to protect the astrounaut. The feasibility of utilizing an actively pressurized bladder system in conjuntion with a full pressure helmet was also demonstrated with the IVA assembly.

Two prototype suits were fabricated during the 18 month program. The first, (Phase B) was completed in May of 1969, the second (Phase D) in December of 1969. As expected, marked improvement of the Phase D suit over the Phase B suit was noted as personnel working on the program gained experience and successful new innovations were incorporated into the suit design. Major improvements incorporated into the final assembly were as follows: (See Figures 1 thru 3).

(a) Individual bladder leakage and bladder manifold leakage was redured significantly during fabrication.

(b) Aesthetics of the total suit assembly was greatly improved.

(c) Permanent convolutes were added to the suit assembly at all major joints which enchanced mobility of the suit in the pressurized mode of operation.

2.2 DESIGN AND FABRICATION

Table I presents the design and fabrication problem summary. Presented are the major problems encountered during the conduct of the program, solutions arrived at, if any, and possible future solutions to problems still existing, are presented in Section 5, Recommendations.

The most acute problem in the design and fabrication area of the IVA suit assembly is that of developing better bladder and bladder manifolding techniques. Solution of the problem will increase bladder reliability, reduce leakage and decrease bladder suit fabrication time. Development in thia area shall be required if a suit of flight quality is to be ultimately developed.

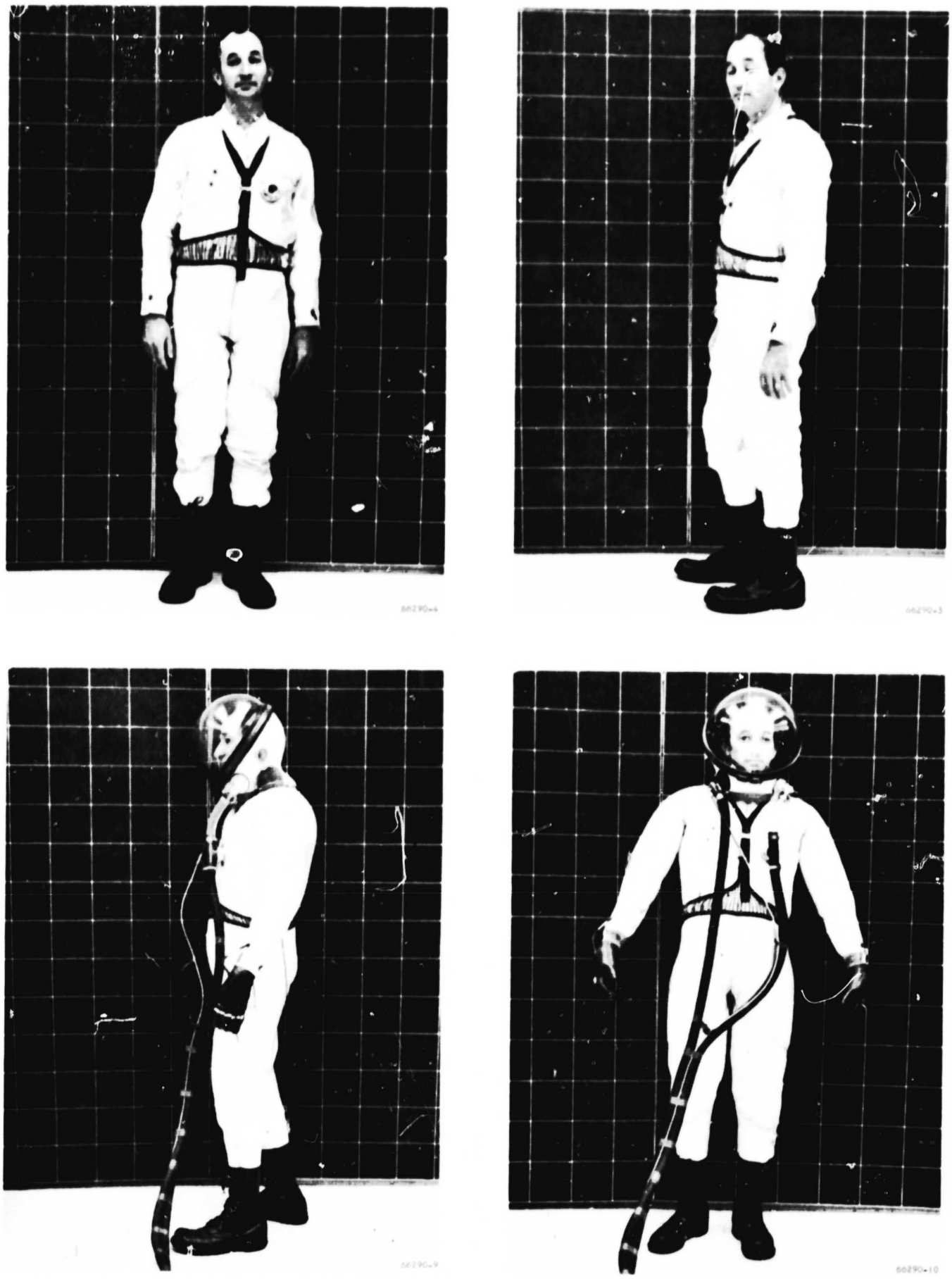

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Figure 1. Phase B IVA Suit - Unpressurized and Pressurized to 1.0 psig

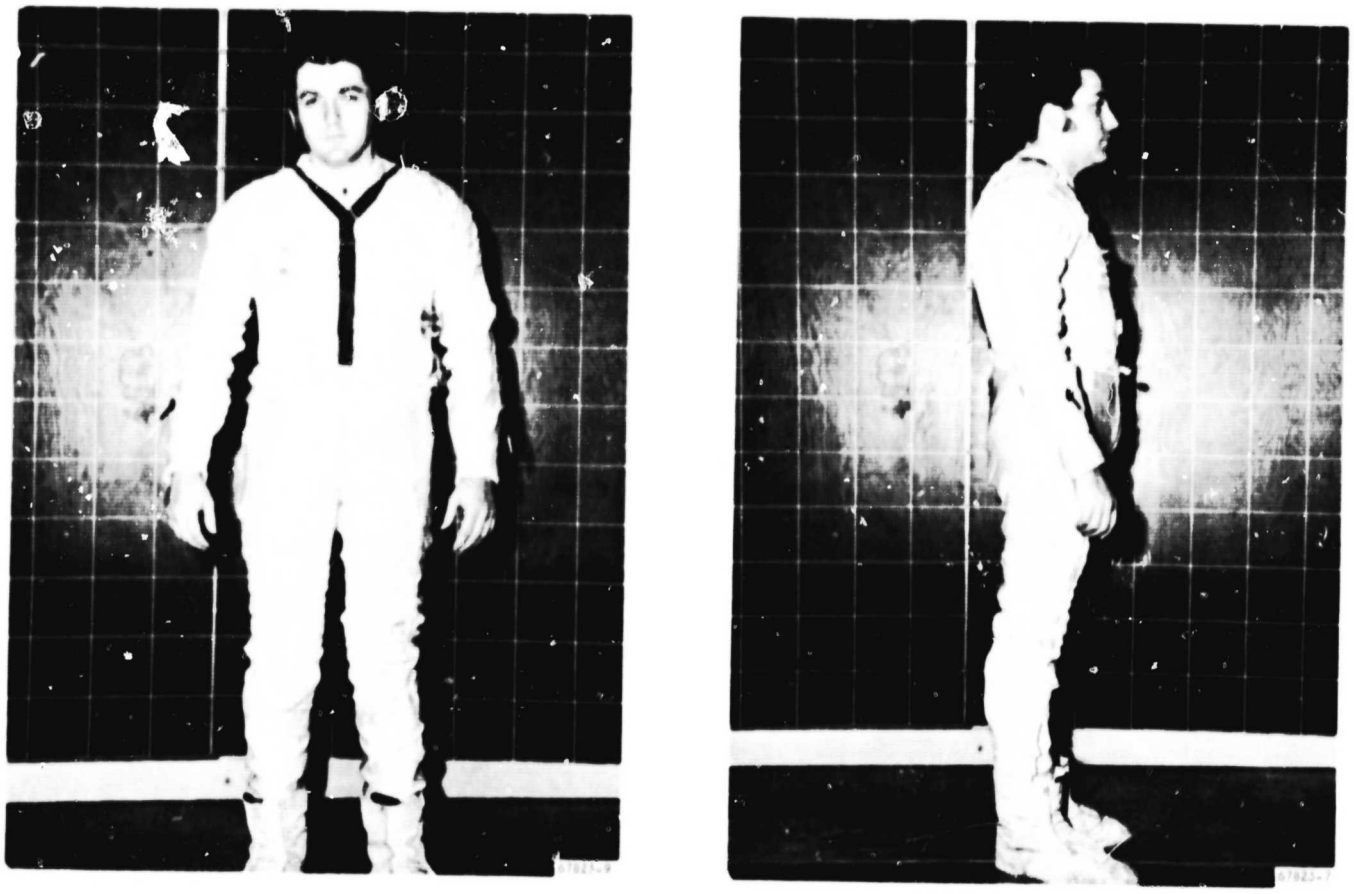

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Figure 2. Phase D IVA Suit - Unpressurized and Pressurized to 3.7 psig

Figure 3. Phase D IVA Suit Pressurized to 3.7 Psig

TABLE I

DESIGN AND FABRICATION PROBLEM SUMMARY

Subassembly	Problem Description	Solution Achieved or Recommended
Inner comfort liner	None	
Bladder suit	Bladder leakage during fabrication of Phase "B" suit	Teflon coating of aluminum strips used in bladder fabrication eliminated sticking of neoprene to the strips and elimainated bladder leakage for the Phase "D" suit.
	Bladder manifolding resulted in hgih leakage due to many contact surfaces (both suits)	Reduced contact surfaces for Phase "D" suit but leaks still present. Further reduction of contact surfaces required and development of sealant for manifolds required.
	Fabrication time of bladders and bladder suit, is excessive	New fabrication techniques need to be developed.
	Inability to obtain 100 percent body coverage in both Phase "B" and Phase "D" suits	Bladder layout on the Phase "D" suit showed a marked improvement over the Phase "B" suit in body coverage and it appears that total coverage can be achieved.
Outer restraint garment	Separation of the Nomex fabric from the seams was noted as the thread cut into the fabric.	Applying adhesive, clear RTV 732, to the seams added reinforcement for the fabric. Final solution shall result in change of fabric material.
	Snags in the garment largely caused by Velcro stripping attached to garment. Loose weave of fabric is part of problem.	Change outer garment fabric material. Possible change of Velcro from nylon to Nomex would prevent snagging.
	The white color of the garment causes the garment to appear soiled.	Nomex material can now be dyed to color desired (royal blue).
	The garment was oversized for the Phase "D" suit and excessive growth was noted when pressurized, causing restricted mobility and inadequate torso counterpressure.	Convolute restraints and torso cinch up lacings helped alleviate the problem. Final solution is proper sizing of outer garment.
Helmet and cape assembly	Bulging of the neck seal Silastic elastomer resulted when pressure was increased to 3.5 psig on the Phase "B" suit	Modification of neck seal design to a saddle arrangement significantly alleviated buldging on the Phase "D" suit. Bulging noted at 4.25 psig.
	Gas diffuser system on Phase "B" suit caused excessive suit pressure drop of 6.0 in. H_2O at 6.0 SCFM gas flow.	Aerodynamically designed gas diffuser for Phase "D" suit only allowed 2.0 in. H_2O pressure drop at 6.0 SCFM gas flow.
Total IVA flight assembly	Restrictive inhalation capability noted with Phase "D" flight suit at pressures above 2 psig causing hypoxia and hypercapnia.	Analysis indicated that relocation of Torso bladder manifolds and possibly increasing number of manifolds would eliminate the restrictive gas exchange of the Torso bladders. Discovered too late in program for modification.

A second problem which requires significant attention in the design area is that of providing a torso bladder suit which allows free gas exchange during breathing cycles such that negative pressure breathing or restrictive inhalation is not incurred. This problem is secondary to the first only because a solution is believed to be closer at hand. Relocating the main torso manifold bladder from the neck to center torso and possibly increasing the amount of manifolds around the torso area will eliminate the restrictive inhalation problem.

2.3 TEST RESULTS

Table 2 presents the IVA suit test capabilities as determined through test at AiResearch facilities. All testing of the assembly was conducted at pressures higher than ambient pressure; unmanned testing at 7 psig, manned testing at 3.7 psig. Program design goals are presented in Table 2 for comparison to the actual test values obtained. As shown, there were many areas in which the IVA suit assembly did not meet the design goals, indicating that further developmental work is required. A primary area in which the IVA suit did not meet expectations was the structural integrity of the suit assembly, not permitting manned testing to 5.0 psig, and proof pressure testing to 10 psig. The suit leakage and pressure breathing as discussed previously were also problem areas. It is believed, and discussed in the recommendations section of this report, that most problems encountered with the suit assembly are not insurmountable and can be solved with further development and testing effort.

Encouraging aspects of the suit assembly were it's comfort and the mobility it afforded in the unpressurized and pressurized modes of operation. Mobility of the elbow and knee joints was encouraging and it appears that emergency crew operations can be performed with the present suit design. Protection to the test subject appears satisfactory, but must be verified through chamber tests, which should be included in the scope of further IVA suit development work.

It appears to AiResearch personnel that sufficient encouragement was gained by the IVA suit program results to warrant further development effort ultimately providing an intravehicular emergency suit that will meet with astronaut acceptance for continuous wear, especially during critical mission phases.

TABLE 2

CAPABILITIES OF IVA SUIT ASSEMBLY

Description	Design Goal	*Actual Test Value
Unrestrained bladder integrity	1.0 psig	2.5 psig
Proof pressure test (15 min):		
Cape assembly	10 psig	4.25 psig
Flight suit	10 psig	7.0 psig**
Maximum operating pressure:		
IVA suit assembly	5 psig	3.7 psig
Leakage at 5.0 psig:		
Cape and helmet assembly	5.0 sccm	Not recorded
Total IVA suit assembly	200 sccm	>9000 sccm
Maximum time of continuous pressurized wear	8 hr	1 hr 4 min***
Maximum time of continuous wear	8 hr	3 hr
Maximum width of suit pressurized (at shoulders)	23 in.	30 in.
Suit system pressure drop at 6.0 scfm and 3.5 psig	4.7 in. H_2O	2.0 in. H_2O
CO_2 partial pressure:		
Man working at 1600 Btu/hr	7.5 mm HgA	Not recorded
Man working at 2000 Btu/hr	15 mm HgA	Not recorded
Maximum weight of total suit assembly	14.8 lb	17.0 lb
Donning time (maximum)		
Flight suit	2 min	5 to 10 min
Emergency 3.5 psig from standby (Requires technician aid)	30 sec	<1 min

*Values obtained from manned and unmanned testing performed at AiResearch at higher than ambient pressures. Testing was conducted on the Phase "D" suit at pressures to 3.7 psig.

**Phase "B" flight suit value, all other values taken from Phase "D" suit.

***5 minutes of which were at 3.7 psig continuous wear.

3. DESIGN AND FABRICATION

Presented in this section are the general design and fabrication features of the various subassemblies with emphasis placed on problem areas encountered during the conduct of the program and their respective solutions. Recommendations for future improvement in the design and fabrication techniques employed are outlined in Section 5, Recommendations.

The IVA suit assembly, consists of the following components or subassemblies:

3.1 DESCRIPTION

3.1.1 Flight Suit Assembly

(a) Inner Comfort Liner

(b) Bladder Suit

(c) Outer Restraint Garment

(d) Boot Assembly

(e) Harness Assembly

3.1.2 Helmet and Cape Assembly

(a) Cape Assembly

(b) Wire Harness Assembly

(c) Bracket, Helmet Hold-down

(d) Helmet mounting Flange

3.1.3 Glove Assembly

MG-1 Flying Gloves Modified

3.1.4 Boots

Gemini G-4C Boots

3.2 FLIGHT SUIT ASSEMBLY

The flight suit assembly (refer to Figure 2, top) is that part of the suit which is worn during normal cabin pressures; it consists of a three

layered suit, which is donned in the same manner as a conventional flight suit. The three layered suit consists of an inner comfort liner, a middle bladder suit and an outer restraint garment. A liquid coolant vest, as test support hardware, provides body cooling during pressurized modes of operation and is worn inside the flight suit. The liquid coolant vest (refer to Figure 4) is used in lieu of a suit integrated cooling system, for lack of funds and development time.

The flight suit is assembled such that each layer can be easily removed for cleaning, and thus the use of velcro stripping and snap fasteners is employed. The bladder suit is completely encased between the inner and outer garments. This was accomplished by the use of white nylon velcro stripping along the frontal location of both the inner comfort liner and outer restraint garment, and around the neck, wrists and ankles of both garments. The bladder suit is held in place within the two garments by the use of commercial snap fasteners. The snap fasterners are located at strategic locations on the bladder suit and are interconnected to the outer restraint garment. Pressure points on the body are prevented by placing snaps on the outward facing portions of the bladders preventing them from contacting the subject. In addition, the placement of snaps is such that pressure points will not be incurred when standing, sitting, bending or rotating the body.

Several entry points to the outer garment are provided. At each wrist of the bladder suit is the interconnection to the partial pressure gloves. The two 1/2" openings at the right chest location are for interconnection to the inlet and outlet liquid coolant vest ports. The entry point at the left chest is the bladder suit gas inlet connection.

3.3 INNER COMFORT LINER

The inner comfort liner is made of nylon trico material, a very lightweight, soft, absorbent material which serves the purpose of providing a comfortable surface to be in contact with the subject. The material is stretchable in all directions and was made to be form fitting and fairly tight. As was stated previously, velcro stripping is sewn to the liner to permit attachment to the outer restraint garment. No problems in fabrication or operation of the inner comfort liner were noted throughout the program effort.

3.4 BLADDER SUIT ASSEMBLY

The bladder suit assembly (refer to Figure 5) consists of 35 striated bladders made of ripstop backed with cured green neoprene E06500, 0.007 in. thick. Curing of the neoprene is accomplished after the bladder is completely fabricated. Once the bladders have been fabricated and cured they are manifolded together to form the bladder suit. Manifolding is accomplished at only six locations on the suit; the neck, both wrists and ankles, and at the crotch area. Each bladder is basically 1 in. wide with a stacked height of 0.20 in. unpressurized. The accordian pleats are 0.45 in. deep and there are two on each side of the bladder. When pressurized, the suit is designed so that the bladder width increases to 2 in. and the dept to 0.5 in. The depth being

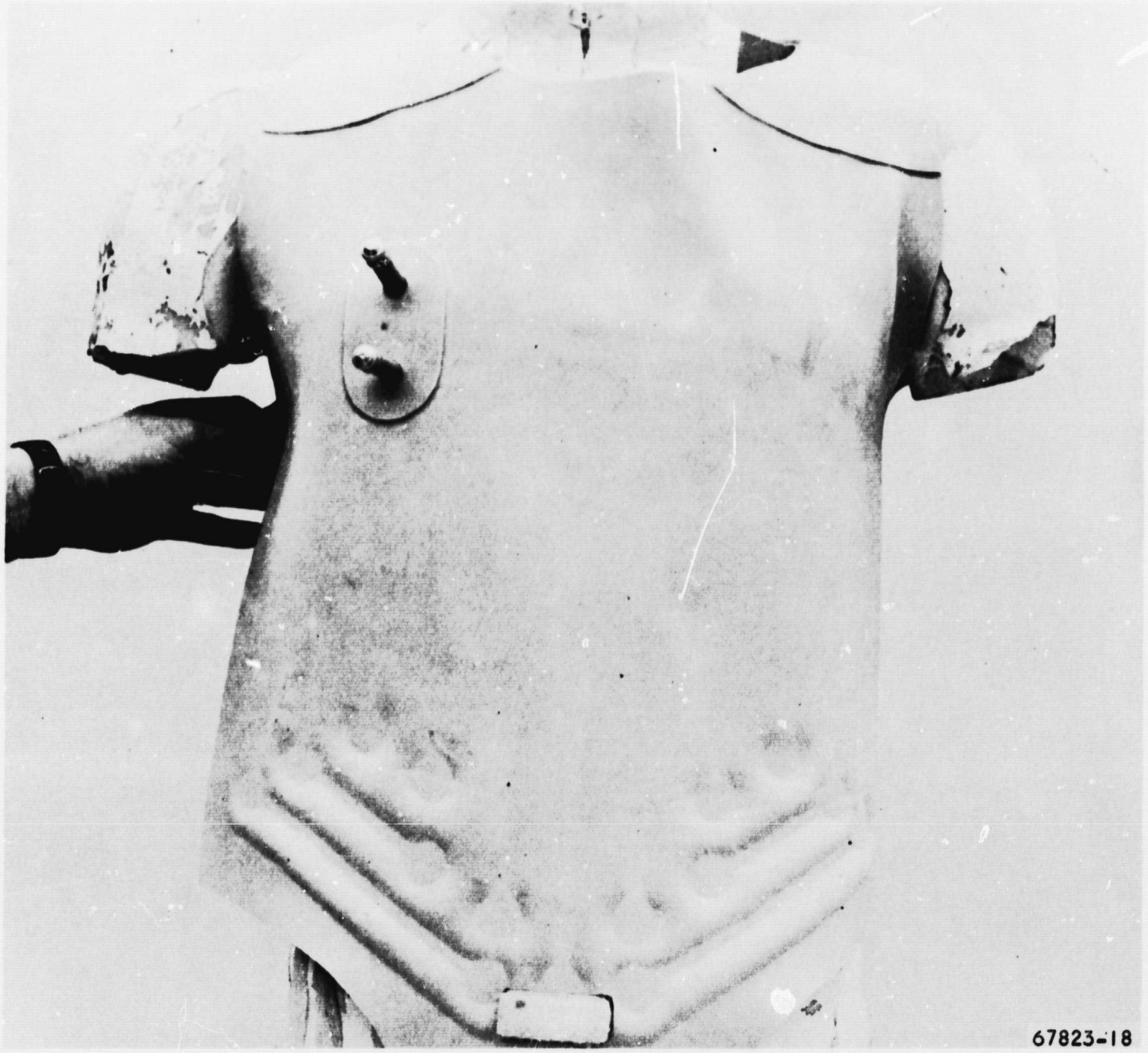

Figure 4. Liquid Coolant Vest for IVA Suit Assembly

Figure 5. Bladder Suit and Inner Comfort Liner Assembly

limited by the outer restraint garment on one side and the wearers body on the other. Width is controlled by the spacing of bladders. The bladders are on 2 in. centers in the unpressurized mode. When pressurized, they expand until they make contact with the adjoining bladder and are thus restrained. Elastic braid attached to individual bladders maintains a 2 in. separation between bladder centers. The elastic braid is made of 75 percent rayon and 25 percent rubber and are 1/2 in. to 3/4 in. wide. The elastic braids are spaced over the bladder suit to maintain the 2 in. separations. Snap fasterners which hold the bladder suit in place snap to the outer restraint garment and are attached to the bladders in a similar manner as the elastic braids. Bladder manifold fabrication was accomplished by placing each bladder into place within the manifold section, installing hard spacer material at the inlet to each bladder and along the manifold to prevent closing of the manifold opening. The bladders are sealed to the manifolds with neoprene adhesive N-136. Sealing of the bladders to the manifolds was a troublesome, difficult and tedious task. First, there was an excess amount of surfaces which required bonding due to the striations in the bladders. This high amount of bonding surfaces resulted in many small leaks. In addition, the N-136 adhesive is air cured, and equal pressure must be applied to the two surfaces to obtain a good bond. The second problem encountered was the amount of manhours required to manifold the bladders and the entire bladder suit. The fabrication of bladders for the Phase D suit alone took 14 man days. The fabrication of the complete Phase D bladder suit including leak checking required approximately 2 man months, which was still considerably better than the Phase B suit, because of the experience gained by the personnel during Phase B and the simplified approach to the bladder suit fabrication of Phase D. The Phase D bladder suit was less complicated than the Phase B suit in that joints at the shoulders, elbows, knees and hips were eliminated. The joint elimination was required because petechia on the test subject resulted from the gaps in the bladder suit and because the mobility hoped for from these gaps did not result. The bladder arrangement of the Phase D suit was selected such that 100 percent body coverage when pressurized could be obtained and the simplest type manifolded suit could be utilized to reduce fabrication and leakage problems.

A third problem noted with the bladder suit was that the cured N-136 adhesive utilized for manifolding bladders, had a 100 to 200 percent elongation before failure resulted. During pressurization of the bladder suit, it was found that several bladder joints were expanded beyond 200 percent. Thus, failure of the adhesive resulted and leaks occurred. The most difficult task facing future development of the IVA suit assembly shall be defining simpler bladder fabrication and manifolding techniques and developing a more reliable leak proof system.

3.5 OUTER RESTRAINT GARMENT

The outer restraint garment (refer to Figures 2 and 3) is made of white nomex HT-22 fabric, a lightweight, highly permeable fabric which offers excellent circulation and comfort to the wearer. The garment is sewn in a spiral to obtain proper stretch along its bias only. Seams are sewn with 40-3 white perma spun, a 10 lb test nomex thread. Sewing is accomplished to obtain the strongest seam possible by using the french cuff technique. The

zippers at the frontal area of the suit, at the wrists and ankles are brass nomex zippers, providing for easy donning and doffing of the flight suit assembly. The velcro counterpart to that on the inner comfort liner is attached to the inner side of the outer restraint garment.

Two disadvantages to using the nomex HT-22 fabric discovered during the program were:

(a) During pressurization of the suit assembly separation of the fabric at the seams was noted. Complete separation and failure was avoided by the application of an adhesive to all the seams of the outer restraint garment. Polyurethane 5716 was used for the Phase B suit, and RTV 732 clear was used for the Phase D suit. The change was made because the 5716 rotted the nomex threads and also the RTV offered a more aesthetic look for the suit.

(b) The fabric weave is fairly loose and snagging of the garment was easily incurred. It appears that some sacrifice of comfort will have to be made to obtain a garment with the desired structural integrity. The sizing of the outer restraint garment was accomplished by obtaining the critical dimensions of the test subject and increasing the circumference dimensions by 3 to 4 in. for the outer garment. This was done to provide easy entrance and exit from the suit and to permit full utilization of the convolutes attached to the outer restraint garment. The oversizing of the garment may have been too conservative because growth of the suit when pressurized appears to be excessive.

Convolutes for the outer restraint garment are formed by loop tape laced with strong nylon lacing cord spaced at 1.0 in. intervals at the shoulders, waist, elbows and knees. Size adjustments for the outer garment was accomplished by lacing up the excess fabric at the sides of the torso, with loop tape sewn to the outer garment on both sides of the torso and lacing with nylon cord. The lacing helped prevent positive pressure breathing as well as minimize growth of the outer garment.

Fabrication of the outer restraint garment presented no major difficulties except that the lightweight fabric utilized was difficult to hold while sewing. Therefore, an additional reason for using a slightly heavier material is that the heavier fabric can be sewn with less difficulty.

The major difficulties of the outer restraint garment can be summarized as follows:

(a) Structural integrity of the garment needs to be improved, both from the standpoint of snagging of the fabric and the separations of the fabric from the thread at the seams.

(b) Excessive growth of the outer garment was encountered which resulted in decreased mobility and ineffective counterpressure. Oversizing of the garment was the cause for this occurrence.

These two problems can be corrected without too much difficulty in a follow-on program; refer to recommendations.

3.6 HELMET HARNESS ASSEMBLY

The helmet harness hold-down assembly is attached to the outer restraint garment at the waist. Loop tape sewn to the outer garment is laced to the buckle and strap arrangement which fits over the shoulders of the wearer and is attached to the helmet brackets. The harness assembly is supported at the waist and the load is distributed over the entire waist by the spacing of the lacing cords in a catenary fashion.

A problem was encountered during test where it was found that the load was not distributed equally at the waist. A pressure point at the right hip was incurred during testing. Increasing the catenary effect at the waist seemed to alleviate this problem and also improved the load distribution.

No other problems were noted with the helmet harness hold-down assembly.

3.7 HELMET AND CAPE ASSEMBLY

The helmet and cape assembly (refer to Figure 3 and 6) provides for attachment to the clear plastic dome, the inlet and outlet gas connectors, the communications system, and the neck seal which permits pressurization of the assembly. The assembly is a full pressure device as opposed to the remainder of the suit, which is a mechanically pressurized partial pressure suit.

The basic assembly is made of nylon ripstop backed with uncured neoprene on the inner surface and nomex HT-3 backed with uncured neoprene on the outer surface. The two neoprene surfaces are laminated together during curing forming a solid sheet. The uncured sections are placed onto a cape assembly mandrel and then cured forming the desired cape shape. Trimming is accomplished and holes are placed into the assembly for the air-lock connectors, the relief valve and the electrical adapter. The neck seal, made of silastic 35, formed to the shape of the cape mandrel and cured, is bonded to the cape assembly with RTV 737 white silicone adhesive and RTV 732 clear silicone adhesive as the fillet material. The inlet and outlet gas connectors, helmet latch assembly, wire harness assembly, gas diffuser system, helmet hold-down bracket and relief valve (set to relieve at 4 psid) are then attached, screwed in place or bonded to the cape assembly as applicable (reference drawing 958260).

Fabrication of the helmet and cape assembly progressed smoothly without major difficulties. Three major changes were made to the Phase D suit assembly after conducting tests with the Phase B suit.

(a) The trim line interface between the silastic 35 neck seal material and the cape fabric was modified to eliminate excessive balooning of the silastic when the assembly was pressurized. During the Phase B manned testing effort it was noted that at pressures of 3.5 psid,

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Figure 6. Phase D IVA Suit Helmet and Cape Assembly

the silastic extruded excessively at the front of the cape assembly and tape had to be used to restrain it. The modification for the Phase D suit was to change the straight line interface between the fabric and silastic to a saddle shape, decreasing the amount of silastic at the front and rear of the cape. A significant reduction in balooning of the assembly was noted for the Phase D suit over the Phase B suit at pressures to 3.5 psid. At pressures above 3.5 psid, specifically 4.25 psid, the balooning became excessive again as the silastic forced its way from underneath the fabric. Stiffeners added to the fabric would probably restrain the silastic effectively.

(b) For aesthetic reasons the material for bonding the silastic 35 to the nomex neoprene-ripstop fabric at the neck seal interface was changed from RTV 156 gray (for the Phase B suit) to RTV 737 white and RTV 732 clear (for the Phase D suit). The change in aesthetic value was apparent and there was no loss in bond strength noted.

(c) The gas diffuser section in the helmet was changed from a makeshift device for the Phase B suit to an airfoil type diffuser design for the Phase D suit, resulting in a pressure drop change from 6.0 in. H_2O at 6 scfm for the Phase B suit, to 2.0 in. H_2O pressure drop at the same flowrate of the new design for the Phase D suit.

The helmet and cape assembly is an effective device which is easily donned and doffed. Minor modification to the assembly to prevent excessive growth, bulging and center offset is required before a completely satisfactory design is achieved.

3.8 BOOTS AND GLOVES

Boots for the IVA suit assembly are normal flight boots. Gemini G-4C boots were utilized with the assembly and were fully adequate for the usage. Gloves are MG-1 partial pressure flying gloves used extensively by the air force. A palmar restraint and finger web cords were added to the gloves to increased protection and mobility. The gloves are pressurized by a football type filler valve which interconnects to the bladder suit at the wrists. The gloves were adequate for this stage of development of the IVA concept.

4. TEST RESULTS

4.1 TEST SETUP

The test setup utilized for manned testing of the IVA suit assembly is shown in Figure 7. The setup consisted of a pressure cylinder containing certified liquid air, a liquid to gas vaporizer for warming the air to approximately 70°F, a pressure regulator, flowmeter, various pressure gages, gas tubing and connectors for the airlock fittings on the IVA suit assembly. Hot and cold lab (tap) water was supplied to the liquid coolant vest through a mixing valve maintaining an approximate 75°F inlet temperature, and 200 cc/min flowrate. Gas flowrate was maintained at 5 or 6 scfm throughout the testing effort. Pressure drop across the suit system was measured from the chest tee inlet connector to the helmet outlet connector. The communications system consisted of a Standard Carter Communication System; Amplifier, Channel Box, and Headsets. A safety feature of the system was the "quick dump" capability provided by the suit gas backpressure valve in case of an emergency.

4.2 TEST RESULTS

4.2.1 Phase B Suit Test Results (Unmanned)

Testing of the IVA Phase B suit assembly commenced on March 26, 1969 and was completed on August 22, 1969. Testing included proof pressure testing of the flight suit to 7.0 psig and manned testing to 3.5 psig. No formal leakage tests of the IVA assembly were conducted as leakage was not a criteria for the Phase B assembly.

Proof pressure testing of the IVA flight assembly was at 7.0 psig and maintained at that pressure for 15 minutes without noted failure (See Figure 8). Stretching of the outer garment fabric seams was noted during the test, but no degradation of the suit's structural integrity or splitting of the seams occurred. It is not known if new leaks in the bladder assembly occurred during the application of high pressure (7.0 psig), as no checks were made.

4.2.2 Phase B Suit Test Results (Manned)

Manned testing of the Phase B suit assembly was conducted during 10 test periods of approximately 30 minutes to 1 hour each. Critical criteria for testing was unpressurized and pressurized comfort and mobility, pressure breathing evaluation, pressure points noted, adequate bladder body coverage when pressurized, and structural integrity of the suit assembly. Initial tests indicated a great amount of pressure breathing by the test subject, not allowing pressures above 1 psig to be attained. Cause for the excessive pressure breathing was found to be from excess outer garment circumference over the torso area and excessive bladder leakage causing a high pressure

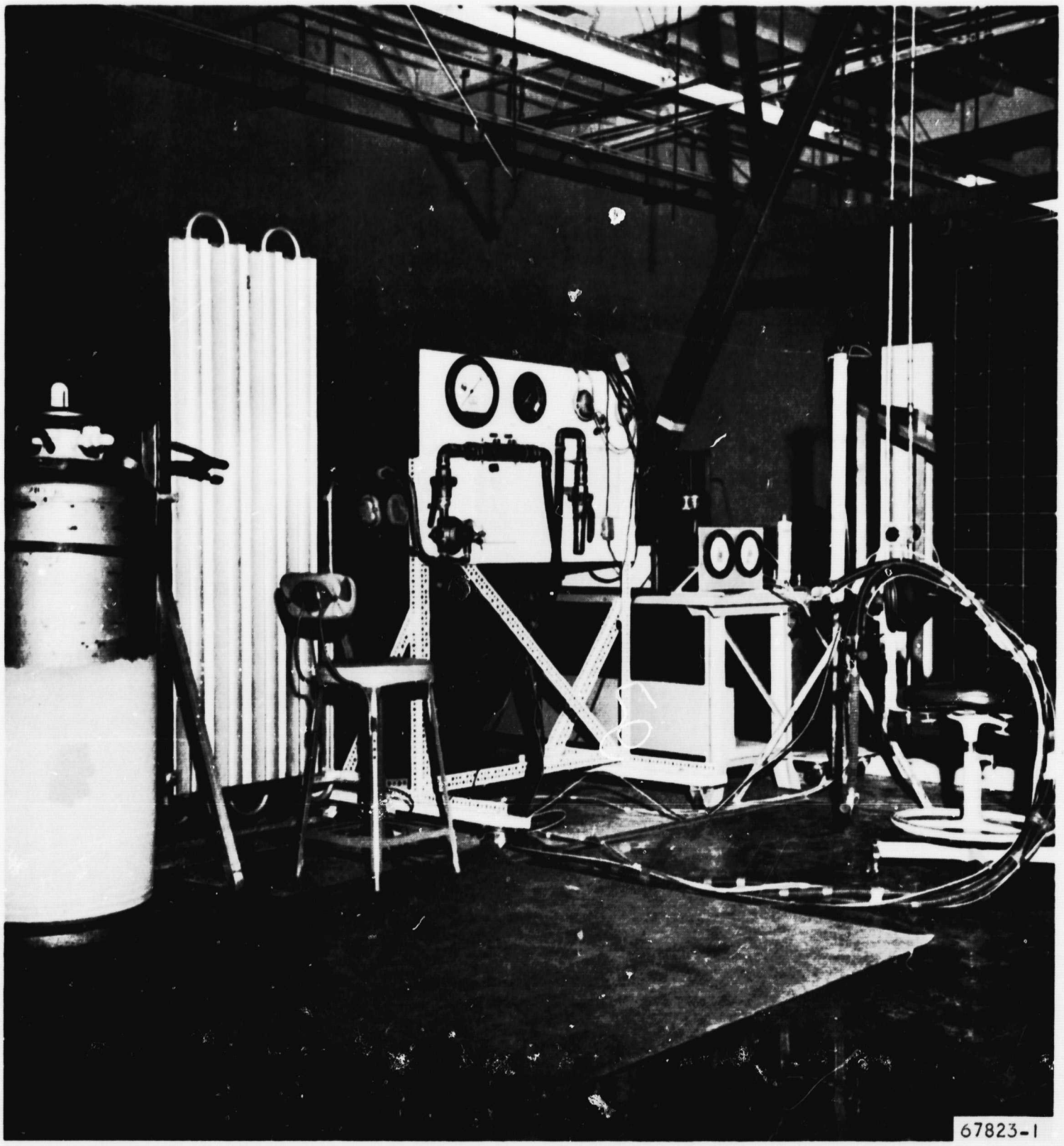
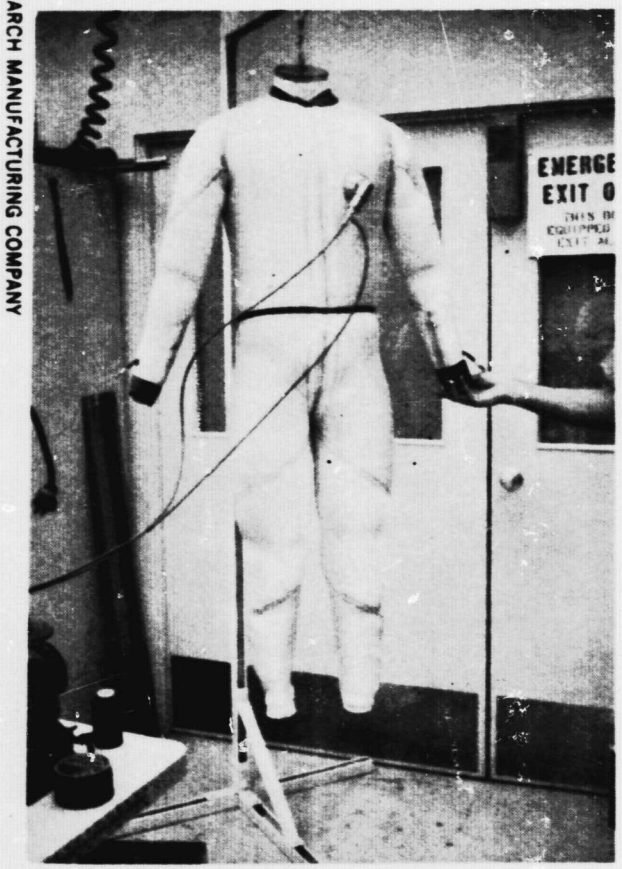
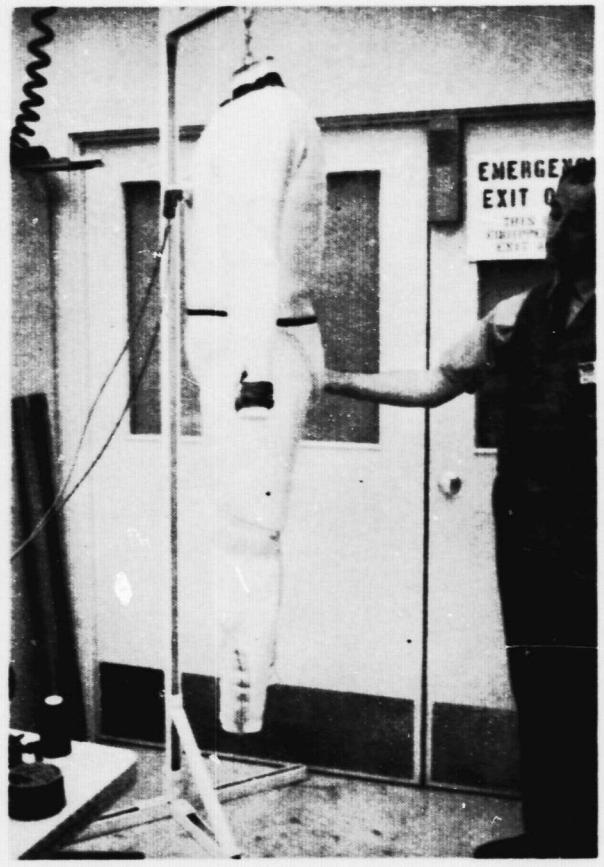


Figure 7. Test Setup





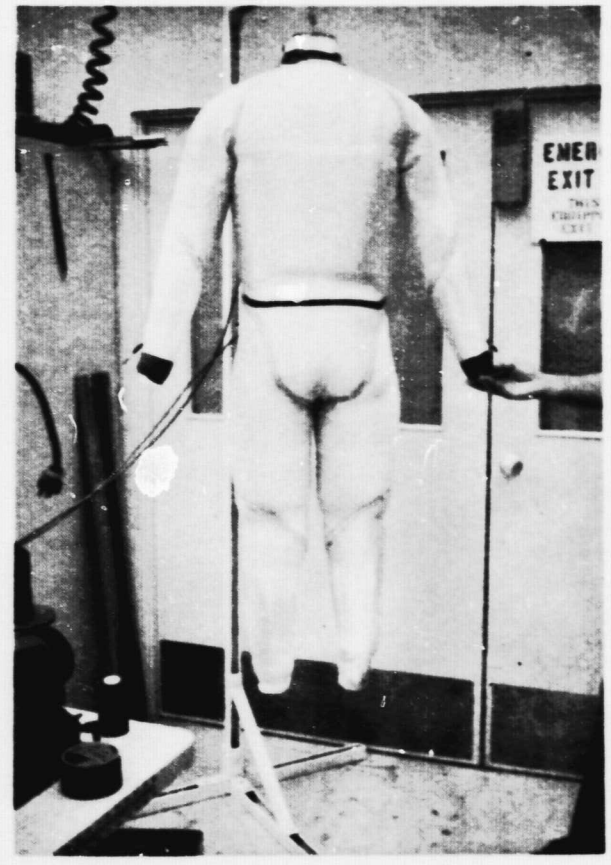


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Figure 8. Phase B IVA Suit Pressure Test at 1.0 psig

differential between the bladder suit and helmet. Repairs were made and pressure breathing was reduced significantly. Suit to helmet pressure drop was reduced to 4.75 in. H_2O at 3 psig and 6 scfm. Maximum time in the Phase B suit pressurized, was 1 hr 2 min, 10 minutes of which was at 3.5 psig. Petechia resulting from testing was noted on the right shoulder and elbow area of the test subject. The subjects fingers had become numb and the problem appeared to be caused by a local pressure point at the axilla caused by tightness of the outer garment.

Total test time of the Phase B suit was 5 hr 49 min, of which much time was spent relieving pressure points on the test subject, obtaining greater bladder coverage by adding new bladders and removing the experimental bladder openings at the knees and elbows. Also, development effort was utilized forming convolutes at the knees and elbows to determine the best method of improving suit mobility. Mobility test data for the Phase B suit is presentd in Table 3. Torque data was obtained utilizing a fish scale placed at the thumb of the subject approximately 14 inches from the elbow center.

TABLE 3

ARM FLEX TEST

	Force, lb			
IVA Suit Pressure, psig	Left Arm No Convolutes	Right Arm Convolutes External Suit	Left Arm Convolutes Internal Suit**	Left Arm *1/2 Convolutes Internal Suit**
0.5	2.5	1.5	0.75	---
1.0	2.5	1.5	1.5	1.0
1.5	3.9	2.5	1.75	---
2.0	3.5	2.5	2.25	3.5
2.5	4.5	2.5	2.75	---
3.0	6.0	3.0	4.0	5.0
3.5	6.75	3.75	7.0	---

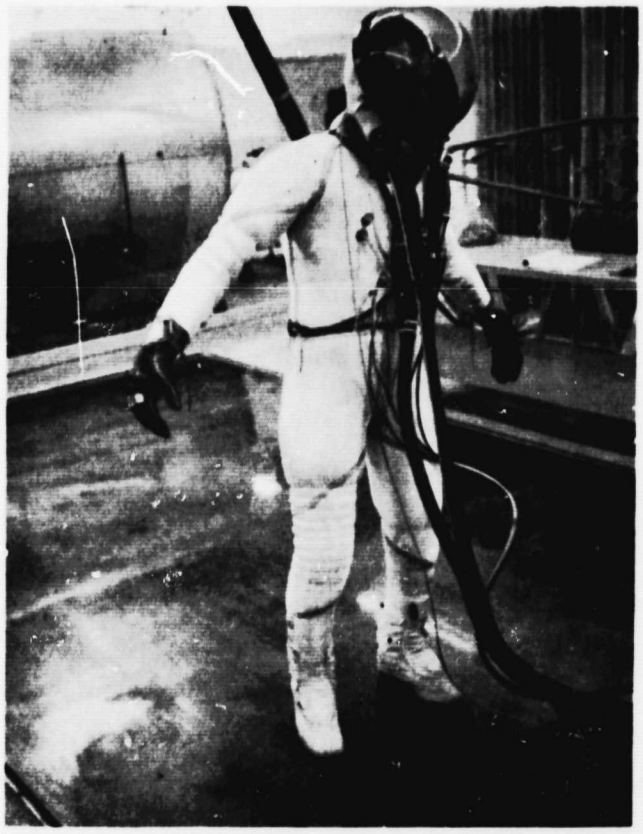
*Half the convolutes were removed from the left arm.
**Convolutes formed on bladder suit, inside of outer garment.

Figure 9 depicts the Phase B convolute techniques tested.

One major problem which limited man testing of the assembly to 3.5 psig was balooning of the cape assembly. This problem was discussed previously in Section 3 of this report.

Inner Suit Convolute Technique

Inner Suit Convolute Technique.
Suit Pressurized to 3.0 PSIG



Outer Suit Convolute Technique.
Suit Pressurized to 3.0 PSIG

Flexibility of Convolute Technique.
Suit Pressurized to 2.0 PSIG

F-11145

Figure 9. Phase B IVA Suit Convolute Development

The Phase B testing effort was a part of the developmental design effort. Testing of new design techniques and the feasibility of the design approach was of the utmost importance during the Phase B effort. Within this scope the Phase B effort was very successful.

4.2.3 Phase D Suit Test Results (Unmanned)

The Phase D testing effort commenced on December 1, 1969 with static leakage and proof pressure tests of the complete assembly. Presented in Table 2 are the leakage results obtained. Table 2 also reflects the Phase D flight suit proof pressure test results. Proof pressure testing of the Phase D suit was conducted with the complete flight assembly, (refer to Figure 10) and pressures of only 4.25 psig were obtained. At that pressure it was found that excessive balooning of the neck seal resulted and the test was terminated. Reviewing photographs after the test (Figure 10, lower) it was observed that the shoulder harness pull down straps could have been positioned more taut, bringing the cape assembly closer to the shoulder and preventing the silastic from protruding, thus allowing higher operating pressures to be obtained.

Other observations of the static pressure tests indicated:

(a) Local separation of the outer garment seams at high stress points occurred, especially at the torso sides and buttocks. Reinforcement of the seams was made by applying an adhesive RTV 732 clear to the seams. Later when torso cinch-ups were added to the suit, the load was transferred from the seams to the loop tape sewn to the outer garment. During manned pressure testing of the IVA assembly, no seam separation occurred. It appeared that high stress points were alleviated by use of the loop tape and lacing arrangement.

(b) Bladder leakage was greater after the proof pressure test. This was due to more than 200 percent expansion of the bladder manifolds when pressurized. The manifold adhesive, N-136 allows only 100 to 200 percent expansion when cured, above this level failure of the bond occurs. Repairs of the bladder manifolds was accomplished by rebonding with N-136 adhesive and then adding nomex-neoprene cuffs to the wrist and ankle manifolds. The cuffs prevented the manifolds from stretching excessively, and no further problems occurred.

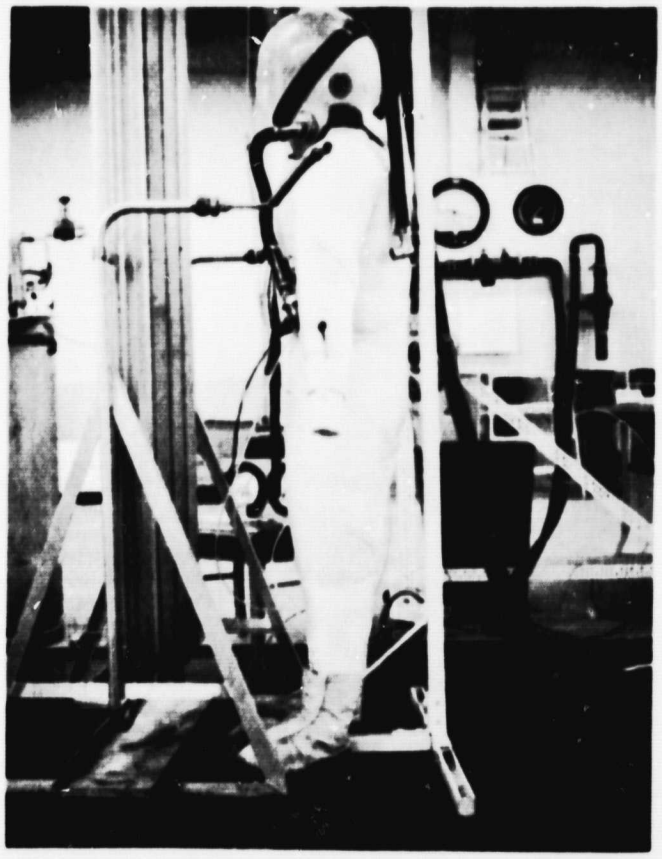
4.2.4 Phase D Suit Test Results (Manned)

Manned testing was commenced on December 16, 1969 with the major task being compatibility of the IVA suit to the test subject. Testing to 1.0 psig was conducted with a total pressurized time of 32 minutes. Problems noted during this test were:

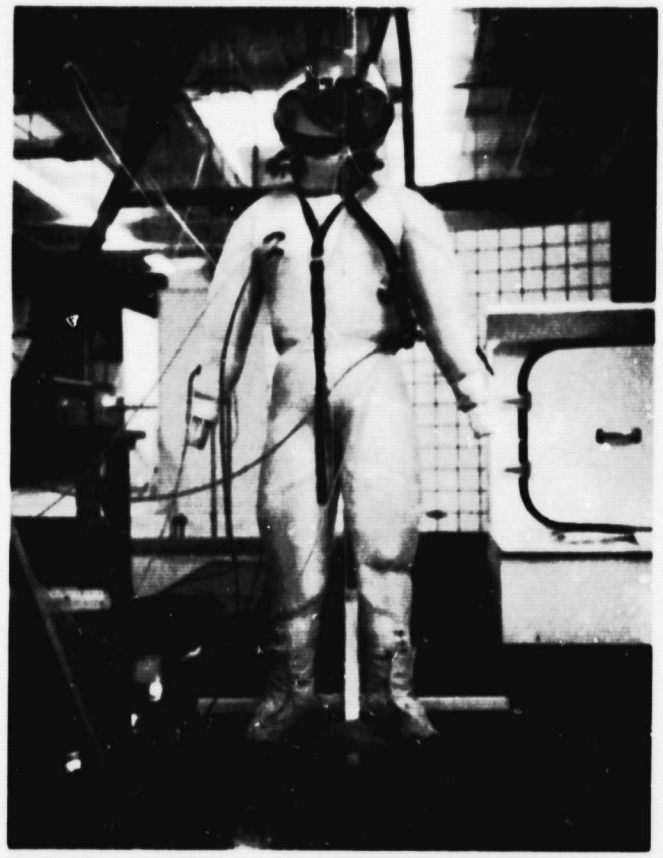
(a) Growth of the outer garment when pressurized.

(b) Poor bladder coverage in calf area.

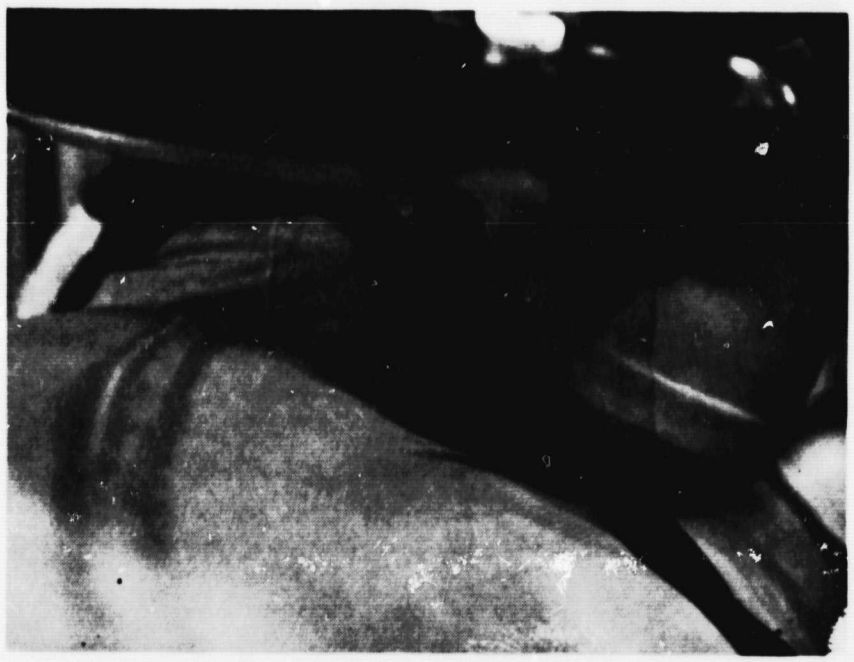
(c) Excessive balooning of bladders at the axilla.



a. SUIT ASSEMBLY PRESSURIED TO 3.5 PSIG



b. SUIT ASSEMBLY PRESSURIED TO 4.25 PSIG



c. BULGING OF NECK SEAL BLADDER AT 4.25 PSIG

F-11397

Figure 10. Phase D IVA Suit Unmanned Static Pressure Test

Correction of all these problems was accomplished before completion of the testing program:

(a) An additional bladder was attached at the ankle manifold of each leg to provide the required calf coverage.

(b) The continuous bladders from the wrists to the axilla and down the side of the body was causing the excessive ballooning at the axilla area. Splitting the continuous bladder and manifolding at the axilla reduced the ballooning significantly but did not alleviate it. Shoulder breadth of the suit when pressurized to 3.7 psig was measured as 30 inches, and elbow breadth at 42 inches, when in the natural position. Elbows can be pulled in to 31 inches.

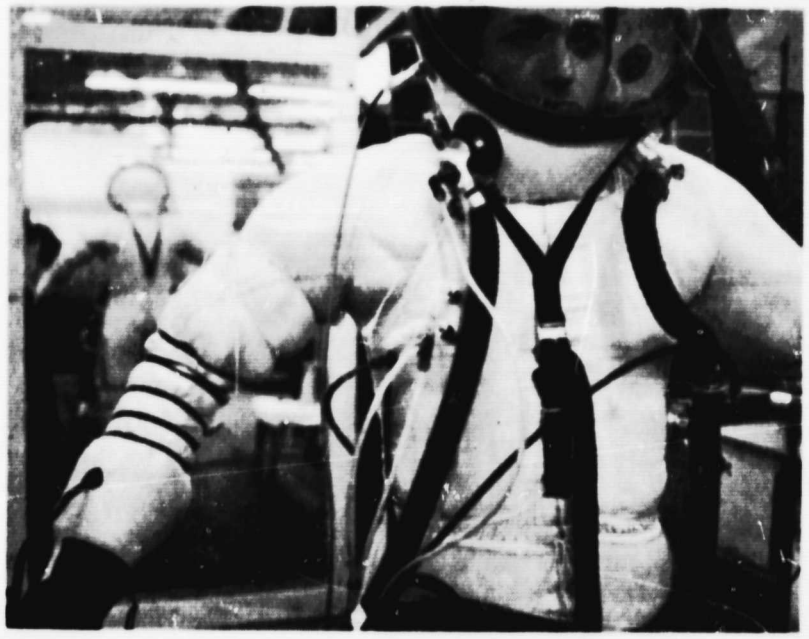
(c) Excessive growth of the outer garment was eliminated by the addition of torso cinch-ups over the sides and waist area, and the addition of convolutes over the suit.

A total of seven tests was conducted with the IVA suit assembly at a total pressurized time of 4 hr 44 min. Maximum continuous pressurized period was 1 hr, including 5 min at 3.7 psig. The longest period the suit was worn continuously, both pressurized and unpressurized, was 3 hr. The longest time in normal flight mode without external cooling was 1 hr 30 min. The subject described the comfort and warmth of the suit in the normal flight mode as being similar to wearing a buttoned snug fitting suit coat in a sitting position. Figures 11 and 12 depict the development of the Phase D suit through the various stages of the testing effort.

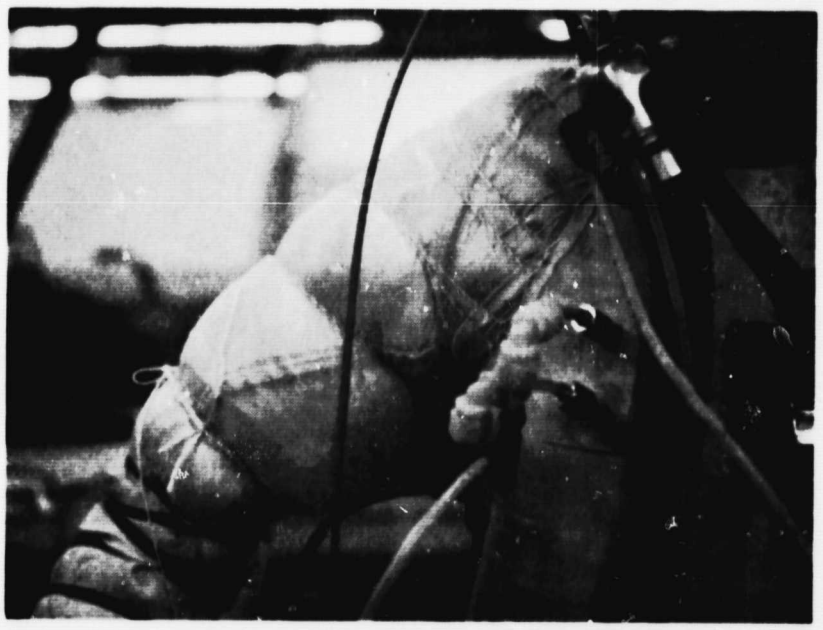
No problems of pressure breathing or petechia were incurred at pressures of 2 psig. Above this pressure, both pressure breathing and petechia worsened. The petechia was incurred on the test subject's neck, arm-shoulder interface and at the elbow joint. All indications of petechia were gone in two days and most had disappeared within two hours of testing. Pressure points on the subject during pressurization were very minor; three pressure points were noted. They were at the right shoulder-neck interface, at the thorax and at the right hip. All were caused by the helmet hold-down assembly force exerted.

4.2.5 Pressure Breathing

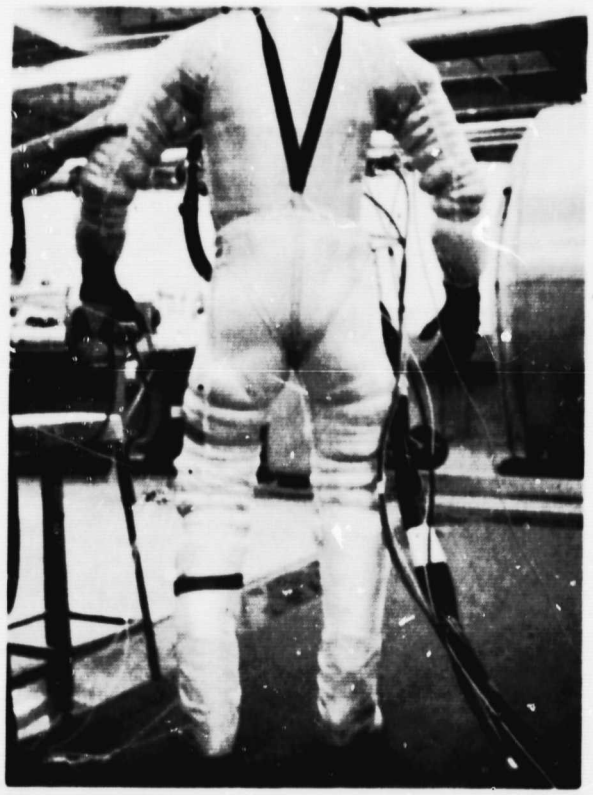
As noted previously the test subject could not sustain pressures above 3.0 psig for more than 5.0 min due to restrictive inhalation. Two subjects were tested to verify this problem. Through description of the phenomenon by the test subjects the following comments were made by the attending physiologists, "The suit becomes very rigid (torso area) restricting inhalation. The subject described it as being able to obtain only 25 percent of the air he desired on inhalation. This phenomenon would result in ventilation of only pulmonary deadspace. Thus there would be inadequate ventilation of the alveoli with concommittant hypoxia and hypercapnia, with the noted resultant dizziness."



e. TESTING TO 2.5 PSIG



f. TOTAL ARM CONVOLUTE DEVELOPMENT



g. FINAL ASSEMBLY PRESSURIZED TO 3.7 PSIG

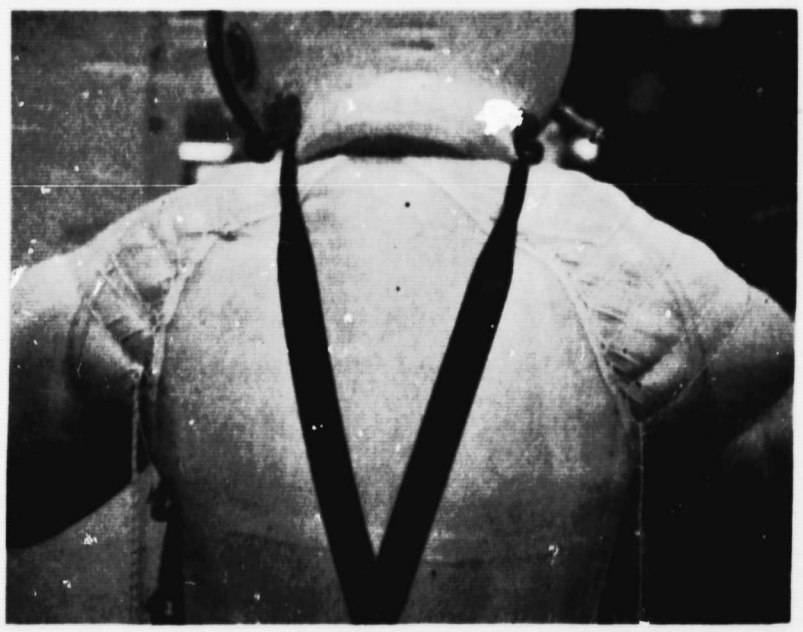
F-11490

Figure 11. Various Development Stages of Phase D IVA Suit

a. ELBOW CONVOLUTE DEVELOPMENT

b. KNEE CONVOLUTE DEVELOPMENT

c. TORSO CINCH-UP STRAPS



d. SHOULDER CONVOLUTE DEVELOPMENT

F-11489

Figure 12. Various Development Stages of Phase D IVA Suit

Several attempts were made at reducing the rigidity of the torso bladders:

(a) The torso cinch-up cords were loosened approximately ? in. on both sides. This appeared to help breathing slightly at pressures below 3 psig, but did not help at pressures above 3 psig.

(b) The liquid coolant vest was removed from the test subject, no effect was noted.

(c) The helmet hold-down assembly was loosened as much as possible, reducing the force exerted on the bladder suit, this helped reduce inhalation pressure breathing at pressures up to 3 psig, but no effect above this pressure.

(d) The hose arrangement to the suit was reversed causing the flow to enter the helmet first and then the suit, rather than in the reverse direction. Four inches of water suit pressure drop resulted, and the subject noted that exhalation pressure breathing was now occurring at pressures from 1.0 psig to 3.0 psig. Above 3.0 psig the inhalation problem again resulted causing termination of the test.

From the above testing it appears that the inhalation problem is caused by restriction of free gas exchange from the torso bladders to the helmet and extremity bladders as pressure increases. Thus, as an inhalation occurs, gas is not being discharged from the torso bladders to allow the chest to expand for complete inhalation. The restriction of torso bladder gas exchange is obviously getting worse as total pressure is increased, this implies that an increasing external force is being applied to the bladders causing the reduced flow area. The only external increasing force applied to the bladder assembly is that of the harness hold-down assembly and cape assembly. The harness assembly is supported at the waist and attached at the cape. The force exerted on the bladders by the cape is located at the neck manifold of the bladders; this force obviously restricts gas interchange through the manifold as pressure increases. Also, the force exerted on the bladders at the waist by the harness restraint, restricts gas exchange betwen the torso and the legs.

The solution appears to be to open up these restrictions by either bypassing the restricted areas, (additional manifolding) or by strengthening the bladders in the restricted area. This can be accomplished by adding space fabric material to the bladders at the point of intersection with the restriction, preventing closure.. The added space fabric material could cause restricted mobility in the unpressurized mode and possibly additional pressure points. The manifolding technique should be tried first to alleviate this problem. A horizontal torso manifold located at the inlet tee connection should be sufficient to eliminate this problem.

4.2.6 Mobility

Pressurized mobility of the suit was not measured quantitatively as planned due to the above mentioned problem. Qualitatively the joint mobility was at least as good as that of the phase B suit presented in Table 3. Range of the

elbow and knee joints were very satisfactory, allowing greater than 90 deg rotation. The shoulder was slightly restricted, not allowing the elbow to be raised above shoulder height. The waist was very immobile, as sitting while pressurized could not be accomplished. Neck mobility was also restricted due to the helmet hold-down straps.

Although many improvements can and should be made to increase mobility, the present suit appears to be satisfactory enough to perform emergency type operations within limited movement requirements.

Unpressurized mobility of the suit is completely satisfactory for performance of space station activities, as reflected in Figures 13 through 16 demonstrating unpressurized mobility.

4.2.7 Donning and Doffing

Donning of the flight suit can be accomplished by the wearer completely unaided. Required suit donning time varies between 5 and 10 minutes. Only difficulty encountered is caused by suit material snags, a direct result of poor suit donning preparation. Doffing the flight suit can also be done unaided. Time required to doff is less than two minutes. Preparing the suit from flight readiness to emergency condition requires less than 1 minute when aided by a second person. The suit at present does not permit self donning emergency readiness. The helmet hold-down straps as presently designed cannot be secured in place unaided. This problem can be eliminated simply by increasing the opening of the helmet hold-down bracket permitting easier entrance of the strap. The glove bayonet type fill valves cannot be attached unaided as neither connection end is held stationary, and the subject being able to work with only one hand. Securing one side of the connection would allow attachment with one hand.

Figure 13. Phase D IVA Suit Unpressurized Standing Movement Capabilities

Figure 14. Phase D IVA Suit Unpressurized Stepping Capabilities

Figure 15. Phase D IVA Suit Unpressurized Sitting Capabilities

Figure 16. Phase D IVA Suit Unpressurized Sitting Capabilities

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The concept feasibility of an actively pressurized mechanical partial pressure suit was proven through the conduct of the IVA suit program. However, continued development effort is required to design and fabricate a suit of flight quality. Additional effort in the following problem areas is required: fabrication of the bladder suit, pressure breathing, unpressurized and pressurized comfort, pressurized mobility, and structural integrity at 5.0 psig and 10 psig (proof pressure).

During the conduct of the program, while attempting to eliminate pressure breathing, excess balooning of the outer garment and improving suit mobility, an effective and significant suit sizing adjustment technique was developed. This sizing technique consisted of adjusting the lacings over the shoulders, arms, legs and at the sides of the outer garment making the suit adjustable for subjects of various dimensions. This sizing capability eliminates the necessity for special sizing of suits for individuals during production, substantially decreasing the overall costs.

Petechia, it appears, shall always be a result of pressurized wear with the mechanically pressurized suit. Although this condition is unattractive, it is not in itself harmful to the wearer. Manned chamber testing at evacuated pressures is required to evaluate if satisfactory counterpressure from the suit assembly is applied to all areas of the body. The higher than ambient pressure testing conducted to date indicated that satisfactory counterpressure was applied.

The development and testing effort conducted on the IVA suit concept by AiResearch does not conclusively indicate that an astronaut acceptable final flight assembly can be developed. But, indications from testing with the Phase D assembly were encouraging, and the improvements noted over the Phase B assembly indicated that the program was proceeding in the right direction. Present indications are that further development is needed and should be conducted before final evaluation of the IVA suit concept is made. AiResearch feels that an affirmative conclusion shall be reached.

A major problem as discussed in Section 4, test results, is that of pressure breathing which resulted in inadequate ventilation of the alveoli thus causing hypoxia and hypercapnia. This problem, if analyzed correctly in Section 4, should be easily solved within the scope of a follow-on program as described in the recommendations. The problem, however, did not permit measurements such as mobility at pressure to be recorded quantitatively. Qualitative estimates of mobility indicated that it was as good if not better than those

values recorded for the Phase B suit. It appears that all emergency flight mobility requirements can be satisfactorily accomplished with the IVA suit with the exception of waist mobility. Further development effort in this area is required to permit the wearer to remain comfortable in a sitting or standing position.

Discussed below are recommendations for a continuing development effort of the IVA suit concept. These recommendations, if carried out, shall hopefully resolve any questions of the validity of the design approach.

5.2 RECOMMENDATIONS

The logical next stage of development for the IVA suit is two-fold:

(a) With limited changes to the Phase D suit design, (outer garment material change, bladder manifold relocation and minor changes for vacuum chamber safety reasons) a new suit should be fabricated and testing conducted in a man rated vacuum chamber. Chamber runs up to six or eight hours should be conducted to prove-out the physiological compatibility of the suit.

(b) Sophistication of design, increased reliability and mobility, and comfort should be undertaken in a parallel effort to the chamber test suit effort. Compartmenting lower torso bladders from upper torso bladders would allow usage of the IVA suit for maintaining proper blood distribution after cardiovascular deconditioning.

The above tasks should be undertaken in a much more formalized program than the IVA program just completed. Drawings should be issued, and prototype testing of various alternatives should be investigated in depth before fabrication commences. The testing effort should be more encompassing and should be handled in a more formal manner than the program just completed. Included in the scope should be the issuance of a formal test procedure and report, and monthly progress reports in addition to a final report. Complete safety control should be maintained for the chamber test run. Constraints such as traceability of materials, inspection of materials, tooling, and the final product must be adhered to in accordance with requirements for manned testing in a 100 percent oxygen or vacuum chamber environment. Detailed drawings and materials should be issued to NASA in accordance with normal AiResearch standards.

5.2.1 IVA Suit Design Changes

5.2.1.1 Bladder Suit

The bladder suit design and configuration for the chamber test suit should be similar in design (except for torso manifold location) and construction to the Phase D suit so as not to incur too much delay before testing of the suit can be accomplished. Thus problems resulting from the manned chamber tests will be detected early in the program and corrections made.

Development effort conducted simultaneously to the chamber test suit effort should be concentrated on the following:

(a) Develop a less complicated bladder fabrication technique. As an example, dipping an aluminum bladder pattern into a latex solution for a prescribed time would build up the desired bladder thickness and shape. This technique could reduce fabrication time significantly.

(b) Develop less complicated bladder manifolding techniques. One approach would be, reduce the number of suit bladders required. For example one bladder each used over both the right and left front torso areas, and only one bladder over the back of the torso, utilizing outer garment cinch-ups over the sides of the body for additional body counterpressure and also as bladder restraints would reduce bladder manifolding significantly. The bladders themselves can be expendables, with high elongation features, which are discarded after one usage. In addition to easier fabrication and reduced leakage, decreasing the quantity of impermeables will aid ventilation of the garment when unpressurized. This technique can also be used over the extremities.

(c) A method of protecting all bladders from failure in case one bladder ruptures, is required. A flow type check valve installed at all bladder manifold interfaces would be an adequate solution to this problem. The development of this type of device requires extensive development effort, as no check valve for this type application exists at present.

(d) Integration of a liquid cooling system into the bladder torso arrangement should be accomplished. This would allow normal convective/evaporative cooling of the body to occur when the suit is unpressurized. The present liquid coolant vest places an impermeable material in contact with a large portion of the torso and effective evaporative cooling is diminished. Integration of water carrying tubes, with sufficient body cooling capabilities into the striated bladders does not present a major problem, but if the bladder arrangement were changed to an expendable bladder system as discussed previously, the complexity of the problem would increase.

(e) Investigate compartmenting the bladder system into lower body and upper body pressurization systems. This feature would allow use of the lower body bladders in a manner similar to current "G" suits forcing proper blood distribution for astronauts and scientists whose cardiovascular system had been deconditioned returning to Earth after long duration missions in a reduced gravity environment.

All facets of desirable design goals must be considered if the final goal is to be achieved. Design trade-offs must be effected to achieve that end.

5.2.1.2 Outer Restraint Garment

As discussed previously in this report the nomex HT-22 fabric utilized for the outer garment was not structurally adequate for the job because of fraying at seams. An investigation into similar but stronger nomex weaves is recommended. This investigation should include recent developed fabrics as well as the possibility of utilizing strengthening fabrics interwoven into the HT-22 fabric. It is recommended that future suits, regardless of the nomex fabric used, by dyed royal blue. This will enhance the aesthetics of the suit as royal blue is less susceptible to discoloration.

5.2.1.3 Helmet and Cape Assembly

The only modification required for the helmet and cape assembly is that of reinforcement of the neck cape. Stiffeners installed into the nomex fabric at and above the silastic interface line will prevent the silastic from bulging when the suit is pressurized. The problem with the present cape is that the force applied to the silastic rubber from the internal helmet pressure is not restrained by the nomex fabric overlap, allowing the silastic rubber to baloon freely. Stiffeners should be capable of restraining the silastic adequately. No problems in donning or doffing of the cape assembly are anticipated by adding to the stiffness of the assembly.

5.2.1.4 IVA Suit Testing

The chamber test suit should undergo the following testing effort:

(a) Initial testing should encompass leakage and proof pressure testing on a manikin.

(b) After successful unmanned testing, the ensuing tests should be conducted with a subject at test pressures to 5.0 psig. Testing similar to that conducted for the Phase D suit should be accomplished.

(c) After successful completion of testing at pressures above ambient, the suited test subject shall be placed in a man rated vacuum chamber, and testing at emergency space conditions shall be conducted. With the suit pressurized to 3.75 psia in a cabin pressure of 200 microns or less, test periods of 6 to 8 hours would eventually be conducted. A physiologist and medical doctor shall examine the test subject after each exposure.

APPENDIX A

A REVIEW OF POTENTIALLY DANGEROUS ASPECTS OF THE USE OF PARTIAL PRESSURE SUITS

Since excellent reviews exist on the need for and development of partial pressure suits (References 1, 2, 3, and 4), only a review of relatively long duration exposure will be made, as they relate to the efficacy of partial pressure protective systems. In addition, since the role of partial pressure suits as anti-hypoxia get-me-down garments using balanced breathing systems is known (References 1, 2, and 3), these potential problem areas will not be considered. Emphasis of this review will be placed on direct mechanical pressure effects on the body, the potential problems of edema and pooling of the blood, and on the phenomenon of ebullism.

The basic premise for the use of pressure suits was reported by Haldane in 1920 when he espoused the theoretical value of a high altitude pressure suit to protect humans above 40,000 feet (Reference 5). The evolution of the partial pressure suit assembly occurred in response to the need for protection against hypoxia at altitude. The advantages of increased air way pressure to raise man's tolerance to altitude functionally was demonstrated by Gagge in 1941 (Reference 6). Gagge was also the first to use a pressure vest for counterpressure for mask breathing (Reference 7). The first complete partial pressure suit assembly was designed and constructed by a group headed by J.P. Henry at the University of Southern California. The suit was tested to a total pressure of 59.5 mm Hg in a hypobaric chamber in December of 1944 (Reference 8). The capstan principle used to tighten fabric on the limbs and thus deliver suitable limb counterpressures was developed to a fully operational concept in the MC-3 and MC-4 series suits (References 9 and 10). Since the development of these suits, the emphasis has switched to the development and use of full pressure suits. Programs have continued in such areas as the development of get-me-down suits such as the CSU-4/P (Reference 11).

A new approach to partial pressure suit design has been suggested by Davies at the USAF School of Aerospace Medicine (Reference 12). This suit design used the Boyle's law expansion of gas with decreased pressure in a series of sealed rubber tubes to develop the counterpressure on the skin. Another new approach is the elastic leotard of Webb (Reference 13). The feasibility of approach of both the leotard and Boyle's law suits has yet to be proven.

The partial pressure suit from its inception has been regarded as primarily an antihypoxia suit and secondarily poor protection against fluid vaporization above Armstrong's line (53,000 ft). They were developed as emergency garments for operational use only if cabin pressurization was lost. Since they were designed for operational aircraft only, the length of time they would be used was determined by the flight duration of the aircraft. Initially, suits were to be used on B-36 bombers but were never flown operationally for that purpose and, in fact, were never used in any multicrew bomber aircraft. Thus, the

suits were used with fighter aircraft and certain special reconaissance aircraft. As a result only relatively short duration expsoures have been realized with the exception of hypobaric chamber testing and several special projects. Information on effects of using partial pressure suits over long durations is very sparse but is believed adequate to evaluate the general approach for adequacy of protection for periods of up to several hr.

The general problems associated with partial pressure suits have been revised by Ritzinger and Aboud (Reference 14). These include poor comfort characteristics, very poor mobility, no ventilation, the requirement for extensive fitting of the suits with long donning times, and very poor integration with other flight equipment. The principle involved in the capstan pressure suit produces a very rigid suit with very poor mobility. The requirement for a tight fitting suit with pressure applied by pulling the fabric tightly over the skin can only lead to discomfort, decreased heat transfer (Reference 13), pinching of the skin (petechiation), and the possible occurrence of serious pooling and edema formation in areas of the body where counterpressure is not applied.

The formation of petechiae and actual pinching is the effect most often seen with partial pressure suit use (References1, 2, 3, 9, 10, 11, 12, 13, and 14). Petechiation normally occurs over the bending surfaces of the body and particularly over the front of the shoulder and in the axilla. MC-3A and MC-4A suits were worn for periods of 2 to 5 hr at 100,000 ft (Reference 10) with no real adverse effects. Only petechiation was noted. In addition, a large series of training tests were performed with the MC-3 and MC-4 series of suits at approximately 100,000 ft for periods of 4 to 6 hr with no irreversible problems. These suits have been worn pressurized for several hr in aircraft without adverse effects (Reference 15). Tests with the CSU-4/P quick-don suit were carried out for 2 hr at 100,000 ft. Problems related to poor suit fit, including petechiation, were reported. Mild pain was noted in the hands but this pain was not limiting.

Potential problems also exist with the use of partial pressure suits due to the lack of pressurization of some parts of the body, e.g., the feet, or because of transition of methods of application of pressure to some part of the body, e.g., the hands. In cases where counterpressures are not even across an area, pooling of blood or the formation of edema can occur. Occurrences of this have been reported by Erusting (Reference 1); Wilson (References 11 and 16), who states that prolonged nonpressurization of the feet causes tissue edema and, ultimately, arterial occlusion from high extraluminal pressure with symptoms of ischemia and associated tingling, numbness, and pain; and Webb (Reference 13), who states that the capstan principle suit is time limited by pooling of blood and the accumulation of fluids in the extremities.

Presented below are general considerations of possible permanent damage resulting from the development of edema in areas in an emergency mechanical pressure suit that intermittently failed to receive a proper balance of pressure for successive periods of a few hours.

The feet of a sitting man are constantly exposed to some 60 to 70 mm Hg of pressure, representing the vertical distance from the heart to the floor. Sometimes this leads to severe edema as in the recorded case of a group immobilized for a whole summer day in a hot railroad compartment in France during the German invasion in World War II. In all of these people, there was conspicuous pedal edema due to a failure of normal milking muscular movements. This vanished within 24 hr of their reaching a place where they could exercise and elevate their legs (Reference 17).

The literature is unanimous that in order to get edema, it is only necessary to have a high venous pressure and a good blood flow for a sufficient length of time. Sitting still is one way of achieving this. This seated posture can be made still more effective by wearing a girdle that constricts the thighs, producing a 20 to 30 cm H_2O back pressure. The so-called panty girdle syndrome results, and the patient complains of swollen legs. The cure is to omit the girdle (Reference 18).

Venacaval ligation produces an acute rise in lower extremity venous pressure lasting from a period of days to weeks: With the pressure rise, there is edema of the legs. Eventually, however, the pressure becomes normal as new channels open up for the blood vessels, and, as long as the lymphatics are intact, the edema eventually vanishes.

Prolonged use of a tourniquet at pressure below systolic but higher than diastolic for a period of several hours will also lead to edema. But when the causative agent is removed, full recovery to normal occurs within a few hours.

It is a fact--agreed upon with rare unanimity--that intractable, prolonged edema will most commonly occur when the lymphatics have been damaged together with the vein draining the region, as in a severe thrombophlebitis of the leg.

Mayerson (Reference 19) points out that the lymphatic system is primarily a drainage device, the need for which developed with the evolution of the high pressure circulation. The lymphatics developed to cope with the problem of clearing the tissue spaces of protein that had leaked out of the blood capillaries.

In this sense, the lymphatic system is a homeostatic mechanism. Its role is particularly important when the balance of pressures has been upset. As long as the imbalance persists, the lymphatics cannot operate, for the pressures permitting fluid return are too high. The moment the balance is restored and normal pressure relations are resumed, the lymphatics recommence function and clear the tissue spaces of any excess fluid that has accumulated.

This is especially well illustrated in postmastectomy edema of the arm (Reference 20). It is now recognized that lymphatic malfunction is the most important factor in this condition. It results from surgical elimination of lymphatics, inadequate regeneration, and scarring around these vessels as a result of infection. Another contributory factor is the frequent, accompanying

damage to the axillary veins due to thrombophlebitis. Yet despite extensive and persistent edema that lasts for months, if the limb is massaged by applying intermittent pressure with a pump to an inflatable sleeve for several hr a day, the edema will frequently be dissipated within a matter of a few days. In chronic cases, edema can progress to a further stage and become hard, i.e., instead of free fluid there may be coagulation and fibrous invasion of the distended tissue spaces. Despite this serious complication, often the coagulation can be eventually immobilized with consequent return of normal elasticity.

The rapidity with which edema which has developed without infection and consequent lymphatic involvement clears up shows the transient nature of the condition, and there does not appear to be any reason for anxiety, even if a swelling does develop in the area within a pressurized region of a partial pressure suit.

There will be a progressive swelling since, except when the skin is attached to fascia as in the palm of the hand, stretching occurs and tissue pressure will not rise above a few mm Hg even in severe edema. However, the suit will eventually provide counterpressure and limit further swelling of the region. Thus mobility will be lost, but with the eventual gain of effective counterpressure.

To recapitulate: Pressure imbalance will lead to edema, but if there has been no infection damaging the lymphatics, then, even if the pressure persists for several hr, a return of the region to normal can be anticipated within 12 to 24 hr. There is no evidence suggesting that a high pressure differential will damage the sweat glands.

It should be noted that, in general, 10 to 15 percent of the blood volume, i.e., 600 to 900 cc, can be sacrificed in localized areas of edema without embarrassing the cardiovascular system (Reference 19).

Exposures to altitudes where the total pressure approaches the effective vapor pressure of fluids at body temperature gives rise to the profuse evaporation associated with the formation of water vapor bubbles in tissues, blood vessels, and body cavities. At the nominal body temperature of 37°C, this occurs at a total pressure of 47 mm Hg. Ward (Reference 21) presented a theoretical analysis of this phenomenon and suggested that the syndrone be named "ebullism," which has been generally accepted by the scientific community. In addition the syndrome is also known as "cutaneous emphysema" or "vapo-edema" (Reference 22).

A history of ebullism has been reviewed by Wilson (Reference 23), including the basic work performed on animals. The first reported case in humans was reported in Henry (Reference 8) in 1944. The subject's hand was heated in 48°C water for 5 min, and the hand was then exposed to 59.6 mm Hg (58,000 ft) with sudden swelling to double normal size at 9 min. Such results have been produced many times, and the individual works are reviewed by Wilson (Reference 23) and Ivanov (Reference 24).

In general, the syndrome occurs when:

$$P_M + P_\phi < 47 \text{ mm Hg} \qquad (25)$$

(Interstitial Pressure) + (Barometric Pressure) < 47 mm Hg

However, once bubbles have been formed from water vapor, they are "fed" by the gas tension of the blood and surrounding tissues, so that disappearance of the bubbles may not occur until relatively high pressures have been reached (100 to 200 mm Hg). Reoccurrence of bubble formation on reexposure normally occurs at relatively high pressures, indicating that micro bubbles might still be present.

The symptoms noted with the ebullism syndrome include painless crepitation and swelling leading to the sensations of the skin being stretched, of ants running over the skin, and a shiny appearance of the skin. The onset of symptoms progresses rapidly, and the range of motion of the member is decreased. Even with all of these symptoms, there are no reported post effects to ebullism in man.

The general aspects of the syndrome show that at altitudes as low as 43,500 ft during vigorous inspiration or "negative valsava maneuvers," evidence of transient interpleural vaporization can be shown by X-ray. At 61,000 ft (50 mm Hg total pressure), vapor may form in the lung during normal inspiration. As pointed out by Ward (Reference 21), vaporization of body fluids begins at 63,000 ft. The site of envolvement is determined by such local factors as temperature, hydrostatic pressure, tissue elasticity, solute concentration, and the presence of gas nuclei. The large veins at the center of the body are sites of early bubble formation. Vapor pockets often form in subcutaneous tissue, in the aqueous humor of the eye, and in the brain.

During the review of the large quantity of information pertinent to ebullism, no incident of effect was noted at total pressure equal to or greater than 50 mm Hg. Thus, the problem of ebullism remains somewhat of an unknown but, in the light of absence of data, represents a reasonable risk.

One of the major problems in the development of the pressure suits has been the ability of the suit life support systems to dissipate excessive body heat. It has been proposed that a new approach to thermal control be made for use in an intravehicular pressure suit based on partial pressure suit principles. This approach uses the normal evaporative cooling mechanisms of the body and is accomplished by exposing small areas of wetted skin to a total pressure of about 50 mm Hg while maintaining the essential body total pressure above that necessary to offset hypoxia and vaporization phenomena. The efficacy of such a thermal transfer system appears theoretically sound. However, since small areas of the body will be exposed to low total pressure (50 mm Hg), an evaluation must be made for possible pathophysiological effects endemic to the system and to rule them out or prevent them before accepting the approach for an operational system. Questions which must be answered

include (1) what are the potential effects of differential hydrostatic pressures between pressurized and nonpressurized body surface areas, including local irritation or actual damage to the skin or to subcutaneous tissue, (2) will marked edema result as a function of pressure differentials, and (3) will ebullism, or boiling of the body tissue fluids, occur, and will ebullism be damaging in areas exposed to pressures in the range of 50 mm Hg.

In summary, there is no information to be found which would compromise the design approach for the IVA partial pressure suit. Effects which might be noted with a waffle textured structure on the skin would include petechiation and imprinting of the design on the skin, both of which would be reversible with time.

Mild edema may occur in areas exposed to 50 mm Hg total pressure but would be reversible. Ebullism should be no problem as long as pressures are maintained at 50 mm Hg or greater. If convective cooling is used in the areas where the skin is exposed to the low pressure (50 mm Hg), the dehydration is a possibility with a steep gradient for water transfer. Although not discussed above, this could be a troublesome phenomenon. The following statement was made by Dr. J.P. Henry of the University of Southern California, the designer of the first capstan partial pressure suit and an authority on aerospace physiology:

"As matters stand, I am not aware of any theoretical physiological contra-indication to the use of the partial pressurization principle in emergency high altitude devices. Twenty-five years of field experience with the partial pressure suit supports the conclusion that no serious and lasting disturbance of skin or subcutaneous tissues develops, despite the often times alarming appearance of the subject on first removal of the equipment."

Even though it appears that a reasonable amount of data is available on potential effects, scientifically one cannot be completely satisfied. As Schueller (Reference 26) states, "For the development of comfortable garments, a systematic study would be of great value to define for various durations of exposure (minutes, hours, days) the maximum of the single area elements on various parts of the body that can be exposed to vacuum without excessive or irreversible damage to the skin or body."

Such studies should include:

(1) Ratio of skin covered to skin uncovered

(2) Studies of optimization of shape and garment configuration

Schueller suggests that fabric or mesh pore size may need to be based on cellular size for long duration exposures, but for short term could be much larger. Each of these variables must interact with each other and with the total design pressure to determine the optimum design based on these few physiologic criterion.

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