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16. Abstract

This report describes the development of a series of prototype Space Activity Suit (SAS) assemblies. The SAS is a new type of pressure suit designed especially for extravehicular activity. It consists of a set of carefully tailored elastic fabric garments which have been engineered to supply sufficient counterpressure to the body to permit subjects to breathe O_2 at pressures up to 200 mm Hg without circulatory difficulty. A closed, positive pressure breathing system (PPBS) and a full bubble helmet were also developed to complete the system. The ultimate goal of the SAS is to improve the range of activity and decrease the energy cost of work associated with wearing conventional gas filled pressure suits.

Results are presented from both laboratory (1 atmosphere) and altitude chamber tests with subjects wearing various SAS assemblies. In laboratory tests lasting up to three hours, the SAS was worn while subjects breathed O_2 at pressures up to 170 mm Hg without developing physiological problems. The only physiological symptoms apparent were a moderate tachycardia related to breathing pressures above 130 mm Hg, and a small collection of edema fluid in the hands. Both problems were considered to be related to areas of under-pressurization by the garments. These problems, it is suggested, can ultimately be corrected by the development of new elastic fabrics and tailoring techniques. Energy cost of activity, and mobility and dexterity of subjects in the SAS, were found to be superior to those in comparable tests on subjects in full pressure suits.

Subjects were exposed successfully to pressures of 20 mm Hg in an altitude chamber. The exposures were of relatively short duration; however, there was no evidence of physiological or physical damage. During the hypobaric tests, physiologically regulated cooling resulted from the free evaporation of sweat through the mesh of the garments.

At the present stage in the development of the SAS, the authors feel, its problems are primarily mechanical in nature. Improvements are needed in methods for donning and closing the garments. Through the use of special fabrics combined with the application ob biomechanical analyses of joint function, it is felt that mobility can be further improved and the energy cost of activity further lowered.

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DEVELOPMENT OF A SPACE ACTIVITY SUIT

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SUMMARY

This report describes the development of a series of prototype Space Activity Suit (SAS) assemblies. The SAS is a new type of pressure suit designed especially for extravehicular activity. It consists of a set of carefully tailored elastic fabric garments which have been engineered to supply sufficient counterpressure to the body to permit subjects to breathe O_2 at pressures up to 200 mm Hg without circulatory difficulty. A closed, positive pressure breathing system (PPBS) and a full bubble helmet were also developed to complete the system. The ultimate goal of the SAS is to improve the range of activity and decrease the energy cost of work associated with wearing conventional gas filled pressure suits.

Results are presented from both laboratory (1 atmosphere) and altitude chamber tests with subjects wearing various SAS assemblies. In laboratory tests lasting up to three hours, the SAS was worn while subjects breathed O_2 at pressures up to 170 mm Hg without developing physiological problems. The only physiological symptoms apparent were a moderate tachycardia related to breathing pressures above 130 mm Hg, and a small collection of edema fluid in the hands. Both problems were considered to be related to areas of underpressurization by the garments. These problems, it is suggested, can ultimately be corrected by the development of new elastic fabrics and tailoring techniques. Energy cost of activity, and mobility and dexterity of subjects in the SAS, were found to be superior to those in comparable tests on subjects in full pressure suits.

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At the present stage in the development of the SAS, the authors feel, its problems are primarily mechanical in nature. Improvements are needed in methods for donning and closing the garments. Through the use of special fabrics combined with the application of biomechanical analyses of joint function, it is felt that mobility can be further improved and the energy cost of activity further lowered.

INTRODUCTION AND HISTORICAL BACKGROUND

This report describes the progress made in the development of a functional Space Activity Suit (SAS) and its related support equipment. The SAS is a protective garment the aim of which is to allow man to function usefully and actively in the vacuum of space. In all space flights to date, astronauts and cosmonauts have worn a protective garment called the full pressure suit (FPS). Basically these garments are anthropomorphically shaped, gastight containers, pressurized to 1/3 atmosphere with oxygen--enough to support life. The FPS may be constructed of multiple layers of reinforced, gas-tight fabrics (soft suit), or it may be a hard suit fabricated of tough, rigid material. Only the soft suit variety has been used in space flights so far. In both suit types, however, complex joint structures are required to permit body movements.

The Space Activity Suit does not pressurize the body with gas, but rather with garments of elastic material under tension, carefully tailored to conform to the body. Oxygen, of course, must be supplied at a pressure comparable to the counterpressure (cp) supplied by the garment to prevent hypoxia and to balance the circulatory system.

What motivated this different approach to protecting a man in space? For the answer to that question we must first examine briefly the history of the development of the full pressure suit and determine how well it performs its job.

In many ways the early history of the development of full pressure suits parallels the development of aviation. In the early 1900's, airplanes, it might be said, were hardly off the ground. Nevertheless, in 1920 J. S. Haldane, in his textbook, Respiration, considered the eventuality that aviators might someday fly above 40,000 feet and require protection against the respiratory problems that would inevitably result from the reduced barometric pressures at such altitudes. Haldane wrote:

> . . . if it were required to go much above 40,000
> feet and to a barometric pressure below 130 mm
> mercury, it would be necessary to enclose the
> airman in an air-tight dress, somewhat similar
> to a diving dress, but capable of resisting an
> internal pressure of say 130 mm of mercury.
> This dress would be so arranged that even in a
> complete vacuum the contained oxygen would
> still have a pressure of 130 mm. There would

then be no physiological limit to the
height obtainable. (ref. 1)

Haldane was, of course, talking about the protection of flyers in airplanes,
but his idea, which was not even tried until 1933, became the basis for the
pressure suits that in the 1960's enabled man to orbit the earth in a space-
craft and eventually to walk on the moon.

In 1933 Mark Ridge, an American balloonist, wearing a modified
British diving suit, successfully underwent decompression in a chamber to
17 mmHg, equivalent to an altitude of 84,000 ft. In the following year the
American aviator Wiley Post, realizing that high altitude might improve his
plane's speed, attained an altitude of 38,000 feet while wearing the third in a
series of pressure suits produced by B. F. Goodrich Co. During the same
period two RAF pilots named Swain and Adam flew a special Bristol 138 air-
craft to record altitudes of more than 49,000 and 53,000 ft. respectively.
They wore Mark Ridge's pressure suit made by the Siebe-Gorman Company
in England. Other pressure garments of various types had been produced
and tested in Europe by 1939; however, all pressure suits produced up to
this time had many things in common. Basically they all consisted of rubber-
ized canvas material pressurized with oxygen. One version used by Pezzi
of the Italian Air Force was electrically heated and even had metal alloy
restraint devices to prevent ballooning. These early suits were awkward,
hot, difficult to put on and take off, and made the wearer virtually immobile.

Just prior to World-War II pressurized aircraft cabins were developed,
and it seemed that the cumbersome full pressure suit would no longer be
needed for high altitude flights. But during the war military aircraft were
designed to fly above 40,000 feet, and some sort of pressure garment was
necessary as a backup in case cabin pressure failed.

In 1945 Gagge, et al (ref. 2), who had studied the effects of explosive
decompression, reported that by breathing oxygen under a few mm Hg of
positive pressure from a mask, men could survive the reduced pressure of
high altitudes without a protective garment. Only 15 mm Hg of positive pres-
sure oxygen was needed for altitudes up to 45,000 ft. This led to the concept
of using positive pressure breathing (PPB), previously restricted to clinical
use, as a.protective device in aircraft, and eventually to the development of
the partial--as opposed to full--pressure garment. With higher positive
pressures (more than 30 mm Hg) unless compensatory counterpressure was
applied to the body there was difficulty in breathing, discomfort in the head
and neck, and danger of circulatory collapse. The addition of breathing
bladders over the chest, as in the RCAF and RAF vests, permitted breathing
up to 30 mm Hg pressure for significantly long periods from an oxygen mask;
however, there was still discomfort in the face and neck. Full helmets were
then added to relieve this discomfort, but now the problem became one of

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circulatory collapse. The raised intrapulmonary pressure caused a marked reduction in venous return to the heart, blood pooling, and then syncope. A helmet and a full trunk bladder extending down over the upper thighs--the RAF jerkin--permitted higher breathing pressures for protection in higher altitudes, but for short periods. It was found that for exposures beyond a few minutes it was essential to add bladders to the legs and then to the arms, which brought on restriction of mobility.

The history of this development and the physiology of PPB are nicely reviewed in Ernsting's book, Some Effects of Raised Intrapulmonary Pressure in Man (ref. 3).

By 1946 American research in PPB and mechanical pressure culminated in the partial pressure suit introduced by Henry and Drury (ref. 4). Added to trunk bladders and the helmet were gas-filled tubes running down the arms and legs, which were tied to the suit material with tapes. When these "capstan" tubes were inflated, the inelastic and tightly fitted cloth of the arms and legs was drawn up tight, thereby applying mechanical pressure to the limbs. An evaluation of the suit was reported by Jacobs and Karstens in 1948 (ref. 5). The suit was intended to give protection against decompression in high altitude aircraft, allowing time to bring the craft down to safe altitudes. For such short periods, nearly complete coverage of the trunk with breathing bladders proved useful, but these bladders plus the anti-G suit bladders on the legs made the pilot hot, since perspiration could not evaporate. The full bladders were used in a later suit by McGuire (ref. 6). Temperature regulation continued to be a severe problem, since more than 50% of the skin was covered by impermeable layers. The suit was useful in aircraft operating at very high altitudes (ref. 7), and it had been tested in a chamber to 198,000 feet (ref. 6), but it was never intended to be used by an active man in a space vacuum.

Another suit developed recently (1967) that uses the partial pressure suit principle is the "passively pressurizing partial pressure suit" described by Davis, et al (ref. 8). An inelastic outer garment covers gas-filled blind tubes running over the limbs and trunk, tubes which expand as the pressure in the aircraft cabin goes down. A partial pressure suit helmet and regulator are used. Volume compensation for breathing is achieved by taking advantage of the large volume available in the expanded tubes running from extremities to trunk.

None of these suits employing PPB and mechanical counterpressure to the limbs was designed particularly for mobility nor for intentional operation in a full vacuum.

Since partial pressure suits cannot be used for extended periods at very low ambient pressures, when the exploration of space became feasible in the 1960's it was realized that full pressure suits would be required to protect the astronauts. Since the requirements of wartime flying had caused all attention to be put on the development of partial pressure garments, no real progress was made in full pressure suits for some 15 years following Wiley Post's first usable suit. B. F. Goodrich did develop another suit in 1943, and by 1950 the David Clark Company was making a full pressure suit, but it lacked an automatic pressurization system and had to be manually adjusted to the desired pressure. Mobility had not been improved much. In 1952 an automatic pressurization device was developed, and since then the drive has been in the direction of increased mobility as well as better temperature and humidity control. Astronauts in the American space program's early Mercury and Gemini flights found no serious drawbacks to the suits aside from their being uncomfortable. But with the first attempts at EVA and doing useful work in space, it became apparent that the metabolic cost of wearing a full pressure suit was very high. In the mid-1960's several groups began the development of hard suits, and they have been used experimentally in laboratories but never in actual space flight. The most recent Apollo suit is in principle similar to the suit that Wiley Post first used back in 1933, with improved mobility due to better joint construction and improved thermoregulation due to the use of water cooled undergarments.

In summary, the full pressure suit has proven itself to be physiologically effective. However, despite considerable effort devoted to the development of special joint structures for both the soft and hard full pressure suits, the energy cost of activity remains high and the wearer's mobility limited. Some typical energy cost values for walking in a variety of recent full pressure suits are given in Table I. As can be seen, the energy cost of level walking is increased from two to three times that expected for the shirt-sleeved subject doing the same work. Mobility, though much improved in recent suits, remains limited, particularly for complex motions involving torso-limb linkages such as the tilting and rotation of the pelvis in locomotion and maintenance of balance.

Since full pressure suits generally burdened the wearer with the drawbacks of limited mobility and increased energy cost, the idea of providing limb counterpressure by means of elastic cloth seemed ripe for further exploration. The idea itself is not new. In the early 1940's J. P. Henry, who introduced the partial pressure suit, thought of the elastic suit concept but did not test it. Some time later, W. E. Hull, at the Aeromedical Laboratories at Wright-Patterson Air Force Base, actually had such a suit constructed, but he didn't pursue the idea further because breathing was uncomfortable and the heavy elastic material then available was stiff and hard to bend. In 1967 Webb Associates gained support for limited testing of the elastic suit concept in a feasibility study contracted by NASA Langley Research Center.

Table I. Some Typical Energy Cost Values
For Walking in Full Pressure Suits

Suit	Walking rate		Energy cost (O$_2$ uptake)		Estimated nude energy cost[1]		Energy cost increase with suit
	km/hr	mph	kcal/hr	Btu/hr	kcal/hr	Btu/hr	
"Apollo state-of-the-art" unpressurized[2]	3.2	2.0	302	1200	225	895	1.34 times
Same, pressurized	0.6	0.4	327	1300	100	400	3.25 "
Same as above	1.9	1.2	453	1800	182	724	2.49 "
Same as above	3.2	2.0	509	2020	225	895	2.25 "
Apollo G20-24 pressurized 3.7 psig	1.3	0.8	293	1163	160	629	1.85 "
Same as above	2.9	1.8	486	1929	210	838	2.30 "
Gemini G-1c-4 pressurized 3.7 psig[3]	1.9	1.2	366	1453	182	724	2.01 "
Same as above	2.4	1.5	498	1979	197	781	2.53 "
Same as above	3.2	2.0	524	2079	225	895	2.32 "

[1] From Bioastronautics Data Book (ref. 9) and Bobbert (ref. 10)

[2] From Roth (ref. 11)

[3] From Roth (ref. 12)

A description of this work can be found in NASA CR-973, "The Principle of the Space Activity Suit " (ref. 13).An arm protected by elastic material was explosed in a special vacuum chamber to 5 mm Hg (absolute pressure) for a period of 20 minutes without incident. Following this, and using in-house resources, a prototype 3-layer suit was constructed to apply up to 100 mmHg counterpressure to the body. Using a partial pressure suit helmet to supply positive pressure air to the subject, a 60 mm Hg assembly was worn in the laboratory for 90 minutes. Mobility and ability to perform useful work were tested using a variety of techniques and found to be extremely good. (Ref. 14 and 15)

Webb Associates was encouraged by these results to continue development of the SAS. In conjunction with the Jobst Institute of Toledo, Ohio, we developed specifications for the construction of a special and very powerful elastic fabric in order to reduce the total number of garment layers required to obtain the needed 1/4 atmosphere cp. At this point the Langley Research Center renewed its support and contracted for development of a complete SAS system including garments and a life support system. It is this work that will be reported on here. Garments supplying from 100 to more than 170 mm Hg counterpressure to the body were fabricated to fit selected subjects and tested in the laboratory at 1 atmosphere; later, subjects wearing the higher pressure assemblies (170 mm Hg) were exposed to ambient pressures of 20 mm Hg absolute pressure (80,000 ft equivalent) in an altitude chamber.

The perfected SAS of the future may ultimately offer many benefits to the space traveller. Reduced energy cost of activity with increased mobility has been cited as the principal goal. In addition, the SAS should be safer and more reliable than full pressure suits since suit rupture would not mean loss of the life supporting gas pressure. A small tear in the SAS garments would leave only a small area of unsupported skin; the astronaut should be able to return safely to the spacecraft without major injury. The life support system could be considerably simpler than those now in use. Thermally isolated from the environment by his full pressure suit and thermal-micrometeorite protective garment (TMG), the present astronaut must be supplied with an elaborate cooling system to eliminate the heat of metabolism. The TMG (which is, of course, also needed with the SAS) could be equipped with shielded vents allowing direct evaporation of sweat on the skin to the surrounding vacuum. The astronaut would receive physiologically controlled cooling much as we do normally. Without the need for a convective gas cooling system or liquid cooling garment, the life support system becomes essentially a tank of oxygen equipped with pressure regulators. In addition to being less bulky and heavy, the SAS system would be much less costly to produce than current garments.

This report reviews the physiological aspects of the SAS approach and describes the development of a series of test garment assemblies and the associated life support system (the SAS system). Test results obtained both on the ground and at reduced pressure are given, and the current and future status of the SAS development is discussed.

PHYSIOLOGICAL CONSIDERATIONS

The Skin and the SAS

The whole body may be exposed to a vacuum for periods of two to three minutes without problem. Hypoxia (lack of oxygen) is the primary time limiting factor. This has been established by exposures of primates and dogs to a nearly complete vacuum, as reported by Bancroft and Dunn (Ref. 16); Cooke and Bancroft (Ref. 17); Koestler (Ref. 18); Rumbaugh and Ternes (Ref. 19); and Stephens, et al (Ref. 20). In the laboratory, Wilson (Ref. 7) exposed human hands to near vacuum conditions (5 mm Hg absolute pressure), and swelling from evolution of gas was not evident until at least two minutes and often as late as eight to ten minutes after exposure. There are a number of other reports of harmless swelling in hands exposed to low pressures--e. g. Ernsting, et al (Ref. 21); Henry, et al (Ref. 22); and McGuire (Ref. 6). It would seem that the skin in its natural state exerts a useful degree of elastic counterpressure, and adding mechanical pressure will prevent gas from forming.

The starting point for the SAS conceptually is that the human skin itself is an ideal pressure suit. The skin is obviously elastic and non-restrictive to motion, but it must also possess the needed strength and gas tightness required for exposure of the SAS-equipped man to a vacuum. Diffusive water loss into space must not be so great as to prevent up to four hours of EVA. Let us examine each of these potential problem areas.

Strength of the skin.--Any elastic fabric used in the construction of SAS garment layers is a network of threads with variable size openings between the threads. In these gaps the skin will be exposed directly to the vacuum. Only the tensile strength of the skin bridging across the network will prevent the extrusion of the underlying tissue out through the fabric. The openings in the mesh of the SAS materials used average approximately $0.5 \, \text{mm}^2$ in area when under tension. The maximum differential pressure existing across the skin in our case should be approximately 170 mm Hg. The actual pressure difference will be a function of the ability of the body tissues to transmit the internal pressurization which originates with pressurization of the respiratory tract. Ernsting (Ref. 3) maintains that even though PPB pressurizes the blood stream to essentially the same level as

the respiratory tract, it does not lead to a general increase in tissue pressure. Tissue pressure under normal conditions has never been satisfactorily measured; however, the fact that some (about 1 cm H_2O) positive tissue pressure does exist has been demonstrated by a number of investigators (Kjellmer, Ref. 23; McMaster, Ref. 24; and Ernsting, Ref. 3). When the SAS furnishes external pressurization and the breathing pressure is adjusted to balance the internal transmural pressure exchanges, the situation is much like that of the SCUBA diver who relies on his regulator to supply the proper breathing pressure as the water pressure on the skin varies with depth. In any case, the transcutaneous pressure when the SAS-suited man is in a vacuum cannot be any greater than the pressure supplied by the garments, since the hoop tensional force on the fabric will constrict upon the underlying tissues until a balance is achieved. At the nominal 170 mm Hg (breathing pressure and garment applied counterpressure), the force acting on the unsupported skin of the man in a vacuum would be 2.3 gm/mm^2. The average tensile strength of adult skin, which derives most of its strength from the collagen fibers in the corium, has been reported to be 1600 gm/m^2 (Rothman, Ref. 25, and Yoshimura, Ref. 26). Even higher values have been suggested-- 2500 -4000 gm/m^2 (Kligman, Ref. 27)--for the stratum corneum alone. The skin, therefore, appears to be stronger by several orders of magnitude than would be required. Since several layers of fabric are needed to supply 170 mm Hg counterpressure, each succeeding layer should effectively reduce the area of unsupported skin exposed to the vacuum.

Gaseous diffusion through skin. -- The passage of gas by diffusion through the skin with an internal-external pressure gradient of 1/4 atmosphere is apparently quite limited. Moyer, et al (Ref. 28) feel that even at transcutaneous pressures greater than 1 atmosphere, the skin remains relatively gas tight. Oxygen loss through the skin into an O_2-free environment is considered to be negligible if it exists at all (Rothman, Ref. 25; Fitzgerald, Ref. 29). Diffusional loss of CO_2 through the skin has been calculated by these same authors to be approximately 100 ml (STPD)/m^2/hr, or about 200 ml/hr for the average man. Although prior to vacuum exposure most of the body's dissolved N_2 would be removed by pre-breathing 100% O_2 (95% of blood N_2 is removed in less than 2 hours of oxygen breathing), the expected percutaneous loss at 1/4 atmosphere gradient is estimated to be only 7.5 ml (STPD)/m^2/hr (Groom and Farhi, Ref. 30). The total loss of the three gases mentioned above would appear to be quite tolerable physiologically. Any losses could be made up by O_2 from the breathing system.

Diffusion of water through skin. -- Water can be lost from the body by sweat secretion and by diffusion through the skin. Sweating may be thermally or psychogenically stimulated; thermal sweating constitutes the principal water loss pathway. Since any sweat secreted in a vacuum would be instantaneously evaporated, furnishing the maximum cooling potential, the thermal demand for sweating should actually produce reduced sweat gland activity.

The actual effect, if any, of a vacuum on sweat gland activity has not been determined; however, there is little reason to believe that function would be other than that which is normal for a given heat load. Similarly, the diffusive loss of water through the skin in a vacuum has not been determined. Extrapolation of curves for insensible sweat loss under hypobaric conditions from atropinized subjects, which may be considered to be mainly diffusive water loss, allows us to predict a maximum diffusive loss rate of 50 gm/m^2/hr for a man in a vacuum (Webb, Ref. 9; Hale, et al, Ref. 31). In the course of a 4-hour EVA, a man with a surface area of 1.8 m^2 would lose (50 x 1.8 x 4) 360 ml diffusively. Evidence indicates that the diffusive loss rate would decrease during a vacuum exposure, since the resistance to diffusion increases as the skin becomes drier, and the superficial horny layer should be maximally dried in response to vacuum exposure. This loss, when combined with cutaneous sweating and respiratory loss, probably would not exceed rates of more than 2 liters/hour, which numerous authors have reported for thermally stressed subjects under normobaric conditions (see Newburgh, Ref. 32, p. 213). This loss rate can be tolerated physiologically by acclimatized subjects for at least four hours (Ref. 32) -- the proposed EVA period.

In summary, it appears from the information available that the skin possesses sufficient strength, gas diffusion limiting properties, and body water retaining characteristics to permit exposure of the SAS protected man to vacuum conditions for a period of at least four hours. This is particularly true if water (and perhaps sweat electrolytes) can be replaced by allowing the astronaut to drink during scheduled rest periods.

The Body Systems and the SAS

Respiration and circulatory balance with positive pressure breathing (PPB). -- Gas must be delivered to the lungs at a pressure sufficient to insure diffusion of oxygen into the blood. A minimal design value is 150 mm Hg when pure O_2 is breathed in a vacuum by an active man. The alveolar O_2 tension at this pressure is 63 mm and the arterial saturation is approximately 90%. This condition is equivalent to breathing air at an altitude of more than 2400 m (8000 ft)--a situation that is quite tolerable. However, since the alveolar O_2 tension is relatively low and there is no safety factor for regulator accuracy, CO_2 buildup, and other potential closed breathing system hazards, we have chosen 170 mm Hg (3.3 psi) of O_2 as the nominal safe PPB for vacuum use. In addition there must be volume compensating counterpressure applied to the chest in order to match the alternating volume changes associated with respiratory movements. Techniques for achieving this with pressurized bladders connected to the breathing supply are well established and were important aspects in the development of partial pressure suits. Some of this history was discussed in the Introduction; however, some additional statements in regard to PPB are needed.

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Routine use of PPB without compensating pressure is limited to 2 - 20 mm Hg for any length of time. With counterpressure on the neck and trunk and partial limb pressurization, as in the British jerkin, positive breathing pressures of 80 mm Hg can be tolerated for 10 minutes, and 140 mm Hg can be tolerated for 1 minute, according to Ernsting (Ref. 3). The partial pressure suits developed by the U. S. Air Force in the 1950's used breathing bladders for respiratory compensation and capstans to draw up the non-stretch suit materials over the limbs and trunk; they provide good protection against decompression but the time of use under maximum PPB is limited. Also, when the bladders and capstans inflate they seriously decrease mobility. The suits are uncomfortable because of uneven pressure distribution and because extensive body coverage by bladders prevents evaporation of sweat. But the greatest drawback has been blood pooling and accumulation of fluid in the limbs when the suits are worn pressurized for longer than 20 - 30 minutes. The capstan partial pressure suit was never designed for prolonged wear pressurized, or for use by active men in space.

As discussed in the preceding section, PPB at 170 mm Hg results in a similar rise in blood pressure. The circulatory system, being a closed fluid system, is thus pressurized everywhere accordingly. In order to maintain balance, matching or nearly matching tissue pressure must be created all over the body. If not, the circulating blood would rush into any low pressure area and pool there. The small veins offer the least resistance to distention and will be engorged if tissue pressure is low. If venous engorgement is continued, the pressure within the veins and capillaries will begin to rise significantly. Once this pressure becomes greater than 10 mm Hg, measurable amounts of excess fluid will be forced through the capillary walls to accumulate in the surrounding tissues. The resulting swelling (edema) and the pooling itself are not markedly uncomfortable, but the sequestering of fluid from the main circulation will result in a decrease in circulating blood volume. Ernsting (Ref. 3) has shown that as little as 200 cc lost in this manner, combined with the psychological stresses of PPB, may cause fainting. Even the most experienced subjects can withstand no more than an 800 cc decrease in circulating blood volume.

In order to prevent significant pooling, the SAS is constructed to provice sufficient counterpressure over the entire body surface to permit use of the selected breathing pressures. In this sense, when the SAS is properly engineered, positive pressure breathing is actually not employed. Considering that the body is accustomed to certain magnitudes of circulatory-tissue imbalances resulting from hydrostatic forces, occlusive body positions, poorly fitted clothing, and the like, the SAS garments may be designed to include gradients, with the counterpressure diminishing distally on the limbs. Special structures under the elastic material are used to fill large concavities such as the axilla and the central back area to help maintain an even distribution of suit applied counterpressure.

Thermoregulation. In addition to respiration and circulatory balance, thermoregulation is the third body system that must be maintained. In the present full pressure suit assembly, the astronaut is thermally isolated from his environment, and radiative thermal exchanges are blocked by a special multilayered reflective garment, the TMG. Since there is no conductive or convective exchange in a vacuum, thermoregulation in a space suit is a problem of dissipation of the heat of metabolism. Presently this job is performed by a liquid cooling garment (LCG) which, while it is more effective than the previously used gas convection method, requires a complex life-support system. Since an astronaut's heat production will be sizable and variable if he is to carry out useful activities, heat dissipation should be rapidly variable and matched to the requirement of maintaining thermal balance. In the SAS, heat dissipation is via the nicely regulated mechanism of sweating. Fortunately, evaporation of sweat is normally a major mechanism of the body which provides precise regulation. The mode by which any water on the skin is allowed to evaporate in the SAS has already been discussed (see "The Skin and the SAS"). The amount of water available for evaporation by cutaneous sweating and diffusion through the skin has been estimated. For each gram of water evaporated, 2427 joules (0.58 kcal) of heat are removed. At the steady diffusional water loss rate of approximately 100 gm/hr (50 gm/m^2-hr), almost half of the resting metabolic heat can be removed. Peak sweating rates of 4 liters/hour, which can be tolerated for short periods of time, can remove 9.7×10^6 joules/hr (2320 kcal/hr) of heat to accommodate short high activity work. Sweat rates averaging 2 liters/hour could be maintained for an entire 4-hour EVA. These potential heat loss rates are well above the anticipated requirements. Therefore it is safe to assume that sufficient cooling is available to satisfy the need for heat removal by the SAS equipped astronaut. Overcooling due to excessive sweating is not likely to occur, since the physiological feedback from cold skin would prevent it. Peripheral vasoconstriction would act to preserve the deep body temperature, if needed. Since all of the water on the surface of the skin will evaporate instantaneously rather than beading up and dripping from the body as it often does here on earth, there is no need for the body to secrete 1.5 to 2 times the sweat required for cooling.

THE SAS SYSTEM

Garments

Design principles and garment engineering.-- In mathematical models the human body is often treated as a series of cylinders and cones arranged segmentally according to the anatomy. This simplified approach may be satisfactory for modelling purposes, but in the construction of form-fitting elastic full body garments in which applied counterpressure must be known

precisely, geometrical irregularities are important considerations. In addition, and in light of the program's objectives, the various joint functions and other body peculiarities must be understood. Types of motions and ranges of movement of different joints must be considered in the design of the SAS assembly.

Construction and design begins with the anthropometric measurements taken from the individual to be fitted. Using techniques developed by the Jobst Institute, a great number of circumferential measurements were obtained concurrently with lengths of limbs. Briefly, the techniques (U. S. Pat. No. 2691221) involve the use of a prepared tape system which has the appearance of a large paper comb. The spine of the comb represents the linear measure and the elongated teeth are circumferential measuring tapes which are spaced at 1-1/2 in. (3.8 cm). All tapes are graduated in 1/8 in. (3.175 mm) increments, and special labelling dictates positioning and the location of selected anatomical features. Once all tapes are fixed in position, the entire measuring device is removed in a single piece by clipping along the closure line with scissors. The circumferences are then recorded by reading the scale figure on each tape where it crosses the starting point. Torso measurements were taken individually with a conventional measuring tape for every inch vertical displacement starting at the top of the leg tape system and ending at the uppermost place around the shoulders. Leg and torso circumferences were ordered according to distance from the floor in the standing subject. Stature was measured as well. Special measurements taken on the torso included the scye and vertical trunk circumference. Neck length and circumferences were also taken. Hands and feet were measured separately with more than 25 measurements of length and circumference taken on each hand. The total number of discrete measurements taken varied somewhat with each subject, but the estimated average number was 150, of which more than 100 were circumferential measurements.

The preponderance of circumferential measurements is based on the need for knowing radii of the various body segments (parts). The pressure to be produced by the elastic material on the subject is determined by the stress properties of the fabric as applied to a given radius according to the Law of Laplace.

For an understanding of how elastic garments pressurize the body, one may use the methodology applied in the analytical determination of simple stress in thin walled cylinders. Engineers usually are interested in calculating "bursting" force in pipes; however, physiologists have used similar techniques in the analysis of elastic properties of blood vessels. In our case, the fact that the constrictive force is applied inwardly does not affect the analysis, since the body is fluid filled, and essentially incompressible. Hence the force may be viewed as that produced by the body pushing out in

accordance with the elastic power applied. There are several shortcomings in this analysis relative to body geometry and pressurization status. Only the perfect cylindrical shape is considered, and the pressurization is static rather than dynamic.
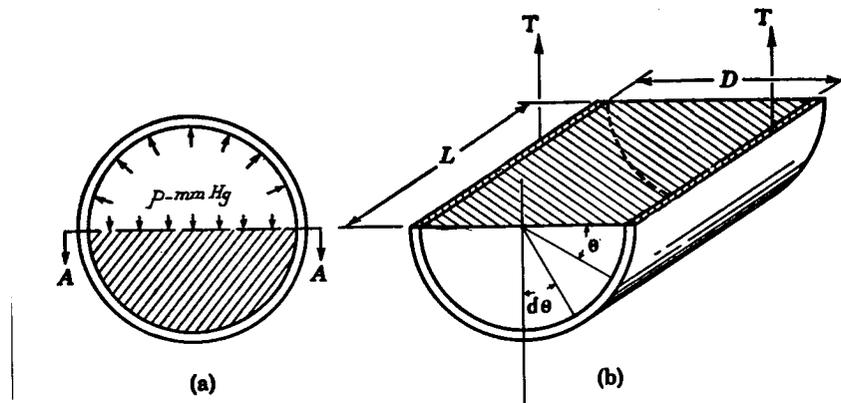
Figure 1.--The diagram used in the determination of the tension forces in a cylinder wall. (After Singer, Ref. 33)

Typically a half cylinder section as shown in Figure 1b forms the basis of the analysis. (Ref. 33) The elementary force acting normal to the cylinder wall located at an angle θ from the horizontal diameter is

$$dF = pL\frac{D}{2} d\theta$$

Since these forces radiate about the entire periphery as shown in Figure 1a and the horizontal components cancel out, the total accumulative force equals the sum of the vertical components:

$$F = \int_0^\pi (pL\frac{D}{2} d\theta) \sin\theta$$

Since the total expanding force (F) acting normal to the cutting surface A-A (Figure 1a) is resisted by equal forces T on each cut plane, F also equals 2 T. Therefore:

$$2T = \int_0^\pi pL\frac{D}{2} \sin\theta \, d\theta$$

and:

$$T = 1/2 \int_0^\pi pL\frac{D}{2} \sin\theta \, d\theta$$

Integrating:

$$T = 1/4 \int_0^\pi pLD \left[-\cos \theta \right]_0^\pi$$

$$T = p\frac{D}{2} L$$

Assuming a unit length and stating in pressure terms:

$$p = \frac{T}{D/2} = \frac{T}{r}$$

where T is equated to the tensional force on the garment and r equals the radius of the part.

The hoop tension developed by the elastic fabric is therefore a direct result of the amount of stress imposed on the fabric when the elongation is fixed at the circumferential length at the particular measurement plane. The elastic modulus (in this case, more properly extensibility) of the selected fabric must be known. This value is simply the ratio of the applied extending force or stress, as expressed per unit of material, to the proportionate change in length from the unloaded value (extensibility ratio). Stress-strain or power curves for the selected fabric are determined on a textile testing machine, and are usually given in terms of percent elongation (as compared to original length of test piece) at a given force (lbs, gms, etc.) per unit width of material (in., cm, ft, etc.). With the properties of the material defined in the above fashion, the circumferential length (hence radius) of anatomical plane known, and the amount of counterpressure to be applied specified, reduced patterns may be made upon which the proper amount of relaxed fabric can be cut.

Several problem areas are immediately obvious. One can see that the amount of tension for a given pressure is less if the radius is small. In other words, a finger is easier to pressurize than the torso by an amount equal to the proportionality of their respective radii. Also, in order for the calculated counterpressure to be applied evenly around the circumference, the body part must be perfectly circular. As stated above, the body is not composed of perfect cylinders. If it were, a careful tailoring job might produce garments with equalization of pressure equivalent to the gas-filled suit. Although in cross-section parts of the body tend to be ovate, ellipsoidal, and irregular, our evidence indicates that garment induced rounding of mobile tissue masses is sufficient to minimize this potential problem. In areas of the body where bones prevent rounding, e. g. the hand, sub-garment rounding devices must be used. If not rounded in these areas the garment will concentrate the counterpressure force on points most distant from the center of the mass. A similar problem, one of gaping of the fabric across concavities, proved to be less than expected. Originally proposed filling devices

such as oil filled bags or "bags of mush" also proved to be generally unnecessary. Also body radii in muscular areas are not constant because of contraction and relaxation in active muscle groups. The pressurization, therefore, varies in amounts dependent upon the amount of change away from the design dimensions used and the position of the fabric on the power curve in the new condition.

The main garment design objective throughout the program was to retain the purity of the original concept of a form fitted leotard. The inclusion of special structures or other variations in the basic garment was considered only after physiological evidence indicated the absolute need. The development of joint structures, for example, had proven with the full pressure suit to be a difficult and costly task.

Fabrics and assembly materials.-- Elastic fabrics may be woven or knitted, and thanks largely to the feminine demands for form-molding, form-persuasive, and foundation garments, a variety of types are available. Elastomeric fibers used today include many kinds of rubber filaments and various synthetics. One synthetic which has found particularly wide commercial usage is spandex, a species within the polyurethane elastomer group. The elastic filaments usually run parallel through the fabric matrix and are held in position by cross fibers of a non-elastic yarn. The method of use to capture the elastic filament often dictates the differential of fabric types and whether it is woven or knitted. This type of fabric possesses largely unidirectional stretch. Any stretch at right angles to the elastic filaments (downstretch) is determined by varying the method of looping, twisting, or tying the cross fibers. Bi-directional or multi-directional stretch fabrics in which elastic elements run in more than one direction are apparently difficult (if not impossible) to make using contemporary textile machines. The elastomer itself may be bare or covered by wrapping with non-elastic yarn. The power of a fabric, or the amount of force needed for stretching, is usually increased through use of larger diameter elastic fibers. However, the power of the finished fabric is the result of a combination of fiber power and the method of knitting or weaving. Rubber yarn (or filament) size is specified in terms of gage or core, which is the reciprocal of yarn diameter in inches. Spandex, like textile yarns, is sized in denier. Denier is an arbitrary term defined as the weight in grams of 9000 meters of yarn.

There are over 20 standard tests used in industry to determine the various physical and chemical properties of elastic yarns. Only a few of these properties determine the elastic characteristics of the finished fabric. In particular the modulus of the fabric is influenced by the size and power of the yarn. The useful elastic range is determined by the maximum elongation of the yarn. The most useful measure of the physical properties of the fabric for our application is the stress-strain or power curve. As mentioned in the preceding section, stress-strain curves are determined on textile testing

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machines in which a known width of test fabric is stretched and relaxed under a known load while a mechanically driven X-Y plotting device draws the appropriate curves on graph paper. Power curves for fabrics used in this project were derived through the use of an incline plane tester (Scott-IP4). The typically sigmoid curve plots stretch in terms of percent elongation above resting length versus force applied in weight or mass units. Both the elongation (stretch) and relaxation curves are drawn during the test. Representative curves are given in Figure 2, redrawn from actual power curves for the powernet and bobbinet fabrics used in SAS construction.
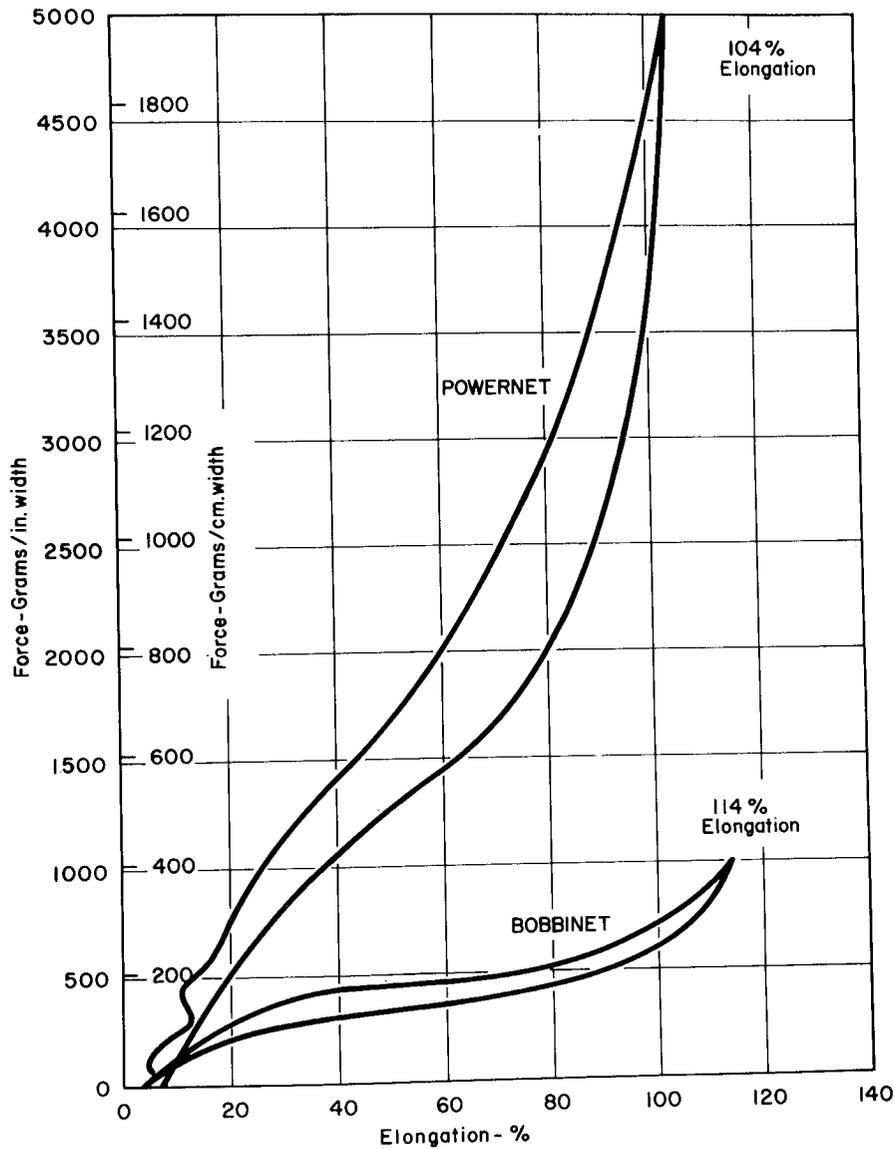
Figure 2. Typical stress-strain or power curves for the two elastic fabrics used in SAS construction.

In calculation of counterpressure to be applied on a given circumference, the power of the fabric is taken from the lower (relaxation) curve. Typically, the variation in stretch and power for a given bolt or roll of elastic fabric may be as much as 15%. Therefore, fabrics used in construction of a given SAS assembly were tested individually. The standard test used a 3 in. wide strip of fabric under a 6 kg load; however, prior to this test the fabric was stressed under double load conditions to the elastic limit to temper the material.

Three different elastic fabrics were used, both singly and in various combinations to produce a variety of assembly layers. The principal fabric used was a type called bobbinet. This is basically the same fabric used in the construction of test sleeves during the feasibility study (Ref. 13). Jobst Institute, the garment fabricator, has found this fabric superior for use in therapeutic gradient pressure garments. The longitudinal elastomeric elements were composed of either 50 gage or 60 gage natural rubber (latex) core, of which the count per running inch of relaxed material was 32. The rubber cores were covered or wrapped in a coiled 140 denier flesh-tone cotton pre-stressing thread set to allow a maximum of 200% elongation. To hold the core in position and give the fabric conformity, a system of interlaced (twisted around core) 140 denier nylon (or dacron) threads was woven on the bias. The geometry of the bobbinet fabric is shown in Figure 3, below.

magnification about 12 x

BOBBINET

(32 cords per inch)
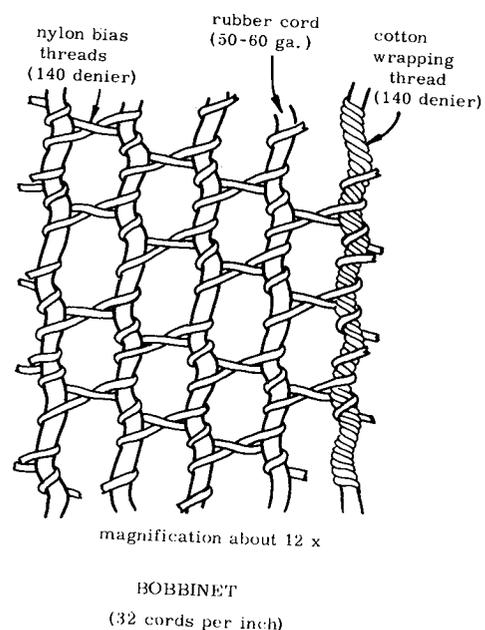
Figure 3. An enlarged sketch showing the arrangement of the elements in the bobbinet fabric.

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The power curves showed a maximum elongation averaging 113% at approximately 1000 gms per inch of fabric. The permanent set for the fabric was 4-6%.

Experience with this material demonstrated that sufficient power was available to develop up to a calculated 15 mm Hg counterpressure on the torso (largest body radii) or as much as 40 mm Hg counterpressure on a wrist (smaller representative radii) while retaining the required stretch well within the horizontal portion of the stress curve and well away from the elastic limit. A general guideline adopted during the project dictated that the pressure to be applied in a single layer not exceed that obtained with 50% of the available stretch.

The second elastic fabric used was a powernet type of material specified by Webb Associates and the Jobst Institute and developed by Liberty Fabrics, New York City in anticipation of its use in SAS construction. In an effort to reduce the number of layers required in a full 170 mm Hg assembly, the fabric was constructed using the largest available spandex fiber (Lycra, DuPont) of 2240 denier. The bare spandex cords were secured by 210 denier nylon fill threads. The fabric composition was 25% Lycra spandex and 75% nylon. The construction detail typical of powernet fabric is given in Fig. 4.

Spandex
cord
(2240 denier)

nylon fill
threads
(210 denier)
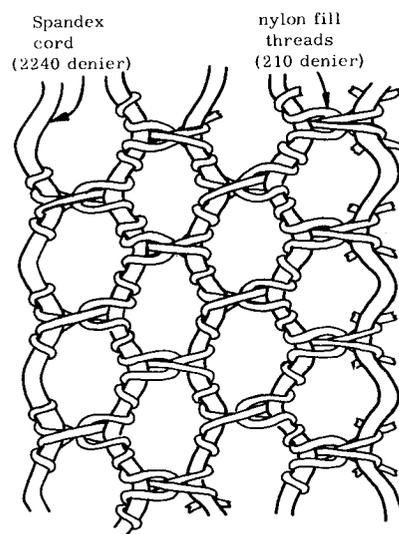
magnification about 12 x

POWER NET

(30 cords per inch)

Figure 4. An enlarged sketch showing the arrangement of the elements in the powernet fabric.

The powernet type of elastic fabric (along with tricot and circular knit) has found widespread use in modern form-persuasive undergarments. This fact is in part due to the fabric's ability to conform to the body during movement. One property--right angle constriction to the line of elongation--was at times a benefit and at other times a detriment in the SAS application. For example, the change in linear distance over the extensor surface of joints during bending caused a concomitant tourniquet effect leading to flexor surface pinching. A grey-green color was selected for its minimum degradation of the fabric during the dyeing process. The average elastic limit for this material occurred at 100% elongation under a force of 5000 gms/in. of fabric (see Fig. 2). It was estimated early that as much as 50 mm Hg counterpressure could be obtained per layer of this powerful material even on the large radius torso. This later proved to be true; however, closure, mobility, and comfort problems ruled out this magnitude of single-layer counterpressure. The selection of spandex as the elastomer was based upon better prospects for future space qualification, although certain spandex fibers contain volatile components which outgas in a vacuum to leave the fiber non-elastic. Spandex generally does provide an elastic modulus superior to comparably sized rubber fibers.

A second powernet fabric found limited use in the several SAS assemblies constructed throughout the project. This fabric was a white, lightweight Lycra spandex and nylon material used exclusively in making low counterpressure foundation layers. The main function of this layer was to provide a smooth, form-fitting surface over which the more powerful layers were slipped. Hence, this layer came to be called the "slip layer." Bio-instrumentation sensors, e.g. thermistors and electrodes, were contained in this layer. The bare spandex core threads were 280 denier and the nylon fill was 100 denier. The maximum available stretch for this fabric averaged from 120-130% elongation. The power factor was approximately 268 gm/cm (1.5 lbs/in.) of fabric.

In preparation for the second phase test program, two special garments were constructed in which the torso portion (heavy powernet fabric) of existing garments was replaced by a 100% Nomex twill fabric (J. P. Stevens Co., Style No. D6151/1). This non-stretch material served to help form the principal helmet and bladder restraint garments of the SAS #10 assembly (see Garment Assemblies). The Nomex fabric, which was a non-stretch material, was selected primarily because of its fire-retardant properties. Woven on the 3 x 1 twill design of 200 denier Nomex yarn, the fabric had a weight of 163 gm/m^2 (4.8 oz/yd^2) and was dyed royal blue. The thread count was 96 and 68 per inch of fabric for the warp and weft threads respectively.

Three types of rubberized fabrics were also used in various capacities. One of these was a neoprene coated nylon stretch fabric, 0.5 mm thick

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(.020 in.) made by the Reeves Co. (style #2613). This material found only limited use as a covering for slip-layer comfort pads. A non-stretch neoprene-nylon twill fabric (Reeves Co., style #5093) was used in the construction of torso pressurizing breathing bladders. The bladders were formed of two layers of this fabric cut to identical patterns, turned rubber side in, and cemented under heat and pressure around the periphery. To insure against rupture under pressure, the inner cement junction was sealed with a 1-in. wide "tape" of the same material. A three dimensional fabric 3 mm thick (1/8 in.) called Trilock (Uniroyal, style #6028-1-1-45) which is often used as a spacing material, was inserted as a liner in the bladders. The function of the Trilock was to prevent a "bottoming" in the bladder due to a maximum respiratory effort or uncompensated counterpressure exerted by overgarments. Subsequently this fabric was found to be unnecessary and was removed. The third rubberized fabric used was a 3 mm thick (1/8 in.), nylon backed foam neoprene material called nyloprene. Since foam was closed cell (unicellular), hence gas tight, this material was used for neck seals and dams. In addition, several prototype bladders were made of nyloprene for use early in the second test phase. Owing to its elastic nature, the nyloprene was found to be unserviceable as bladder material and was replaced by the rubberized nylon fabric originally used for this purpose.

Non-textile materials used in SAS construction, in addition to zippers of various sizes and types, were sheet neoprene rubber, silicone rubber, and plastic foam. The sheet neoprene was used principally as material for gaskets in the helmet; it was also used to reinforce dams. The plastic foam-- flexible urethane--was used to make comfort pads and to fill various anatomical depressions. Pads of 6.35 mm (0.25 in.) thick open-cell foam were sewn into the slip layer to prevent pinching in the axillary area and on the flexor surface of the limb joints. Later versions of the footcovers contained similar pads to fill the posterior malleolar depressions. Rounding pads of silicone rubber (Silastic, Dow Chemical Co. #485) were custom molded for the palmar and volar surfaces of the hands of two subjects. These pads were individually inserted under the gloves in the full suit test configuration.

Garment Assemblies. -- A total of ten different garment assemblies was constructed throughout the project. Of these, three each were fabricated to fit three subjects, and the remaining assembly was partially shared by two of the subjects. The first nine assemblies were fabricated by Jobst Institute, Inc., according to Webb Associates specifications, and numbered consecutively, SAS #1 through SAS #9. The design specifications for these garment assemblies have been included as Appendix A of this report. The final assembly--SAS #10--which consisted for the most part of modified layers from earlier assemblies, was constructed in-house for use in the second testing phase. SAS #1 and #2 were designed to apply a total of 100 mm Hg counterpressure, or, rather, to maintain physiological balance in a man

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breathing at 100 mm Hg. Using methodologies discussed earlier, counter-pressures were pre-calculated for each layer according to the specifications. SAS #3 through #9 were designed so that they could be used in either the 100 mm Hg or the 170 mm Hg counterpressure test configuration, depending on the number of layers used. Many individual layers were designed to include limb counterpressure gradients; these were negative in that the counterpressure decreased distally. Gloves, breathing bladders, and foot covers were included as accessories with each full suit assembly; however, a number of individual garments and partial garments were constructed as test layers for which specifications were not written. Since a complete description of each layer of all of the assemblies would be extremely lengthy, and since early garments were mainly used as a basis for later improvements, only a general description of each assembly and the evolution of consecutive assemblies is given in the following paragraphs. (For additional information, see Appendix A).

The first assembly (SAS #1) was constructed to fit Subject A (see "Subjects"), and consisted of a slip layer of the light powernet material and two full body garments of the heavy powernet fabric. Each of the two pressurizing layers was engineered to supply 45 mm Hg counterpressure to the torso and gradients down to 30 mm Hg counterpressure distally on the limbs. Including the nominal 10 mm Hg counterpressure furnished by the slip layer, the complete assembly was to apply a total of 100 mm Hg on the torso. Closure was by means of zippers (for positioning, see Appendix). Cloth tunnels and pull tabs of nylon twill fabric were sewn along torso zippers to test different closure devices and techniques. After fabrication and final tailoring, fitting trials were performed with SAS #1 (see Appendix A-1) to determine the wearability of the garment. We discovered that closure of high counterpressure (more than 45 mm Hg) powernet layers was very difficult to accomplish, mobility was greatly restricted, and joint pinching with skin abrasion resulted from movement.

As a result of these discouraging findings, additional investigations into design and closure methods were performed. Closure methods using laces, hooks and eyes, and Velcro were tested on various garments. Closure devices were also examined, including levers, laces, and pulling tools. The results were not promising. More complex mechanical assistors were considered, such as compressed air driven clamps, exoskeletal frames, and hydraulic cylinders; however, investigation into the development and construction of complex devices proved that it would have been far too costly and time consuming at this stage in the development. Although these types of donning and closure machines are theoretically feasible for use in the laboratory, they would not readily lend themselves to use in space. Our design objective then became a garment assembly which could be donned and closed using fairly simple devices or none at all. Considered as the best compromise,

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the zipper was retained as the principal donning entry and closure device throughout the project. The development of motorized and/or elastic zippers was rejected by zipper experts as being infeasible, impractical, or too costly.

Following the experience with the first garment, a second 100 mm Hg garment, SAS #2 (see Appendix A) was specified; it used a "divide and conquer" design philosophy in the torso area. By dividing the powernet fabric into 3-in. wide strips which were pulled into position and held to a matching opposite strap with Velcro, it was thought easy closure and donning could be obtained. As much as 50 mm Hg counterpressure per layer was possible, and some adjustment was available by placement of the Velcro patches. An attached, single piece over-layer was positioned over the strap garment to assist in holding the straps in place and to minimize gapping. The full 100 mm Hg assembly was designed with a 100-50 mm Hg gradient proceeding distally down the limbs, and several special joint tailoring treatments were initiated with this garment. Several wear trials quickly demonstrated problems very similar to those experienced with the first assembly. As a result other methods to facilitate donning, closure, and improve mobility were tried. Several special garments or partial garments were designed and constructed to test various ideas. A torso garment with lateral zippers and crotch strap proved to be of little advantage. Another layer, a full body garment, was constructed with dual full length zippers placed along lines of non-extension (Ref. 34). The looked-for improvement was not evident. The strap (tape) layer and its overlayer of this assembly were later modified and used as part of the SAS #10 assembly.

It became obvious that many of our problems resulted from attempting to obtain a maximum counterpressure from a single layer, plus the physical effect of the strong powernet fabric on limiting joint movement. Specifications were then written for SAS #3 (see Appendix A-) in which the use of powernet fabric on the limbs was abandoned. All arm and leg garment segments in this assembly (and all future ones) were constructed of the less powerful bobbinet. A complete 170 mm Hg garment was made, composed of four full body layers and two partial coverage layers. Special tailoring was performed, much of it after initial fittings, in the axillary area and over the elbows and knees (see Appendix). Excess material over flexor surfaces was removed, extra material was inserted on extensor surfaces, and pouches, pads, and longitudinal orientation of cord elements were devised. All full body layers were supplied with laterially positioned limb zippers on proximal and distal segments, and front full length torso zippers. The zippers on the limbs did not cross joint lines and were included to make donning and proper positioning easier. Small nylon fabric (non-stretch) tunnels were sewn along the powernet front torso zipper lines, to which could be attached several types of strap pulleys, slip rings, and hand pulls to assist in closure. These devices were all detachable. Detachability, simplicity, and speed of operation were considered design goals.

Actual wear trials demonstrated that garment assembly #3 was comparatively comfortable and that mobility was somewhat improved. Gloves, foot covers (booties), and a breathing bladder were supplied for the first time. The design of the breathing bladder, which covered much of the torso area, was the same as that constructed for SAS #4 (see Appendix A). The bladder was fabricated of a rubberized nylon cloth. The various positions and connections of the bladder with regard to the breathing loop are described in the Helmet section of this report.

Garment assemblies SAS #4 through #7 were basically the same in design; therefore a description of #4 only is provided in the Appendix. The major difference between this series of garments and SAS #3 was that no pressure gradients were included. The entire assembly in each case was engineered to apply a total of 170 mm Hg over the entire body surface. Many laboratory tests were performed using these garments. The only major on-line modification made was the reduction of limb counterpressure by removing arm and/or leg segments from one or two of the layers. The engineering criterion of retention of at least 50% of available stretch in the donned suit applied to all of these assemblies. This allowed for a maximum of approximately 35 mm Hg/layer on the torso with the powernet fabric, and 15-20 mm Hg with the bobbinet. The limb segments, all bobbinet, could produce a maximum of 30 mm Hg/layer on the thigh, the largest limb circumference.

Laboratory tests up to this point in the project disclosed several factors related to suit design and function. Some of the findings were:

-- A satisfactory reduction in distal limb counterpressure could, if thought necessary, be obtained by simple removal of garment assemblies.

Slit openings in the fabric of all but two layers over the flexor surface of the elbow and knee were allowable physiologically and beneficial for improvement of mobility.

To hold down the helmet, straps could be sewn to the regular torso garments and attached directly to the helmet baseplate.

Reduction of total pressure applied via the garments to the torso, allowing the bladder to assume more of the pressurization duty, made breathing and garment closure considerably easier.

Using the above findings, SAS #8 and #9 were ordered. These garments comprised four power layers which combined to produce a total of 100 mm Hg on the torso, 160 mm Hg on upper arms and upper legs, and 152 mm Hg on lower arms and lower legs. Full arm and leg sections were ordered so that we could continue to experiment with varying limb

counterpressure. The differential between the 100 mm Hg applied to the torso and the 170 mm Hg required breathing pressure was balanced by the bladder expansion. The area counterpressures and layer numbers are listed in Appendix A. A sketch of the hold-down strap arrangement is also given. The joint treatments, zipper placements, and accessory design were much the same as those in the preceding garment.

Given below is a series of labeled photographs which show the suit layer sequence and garment accessories typical of those used in the majority of the first phase tests, both on the ground and in the altitude chamber.
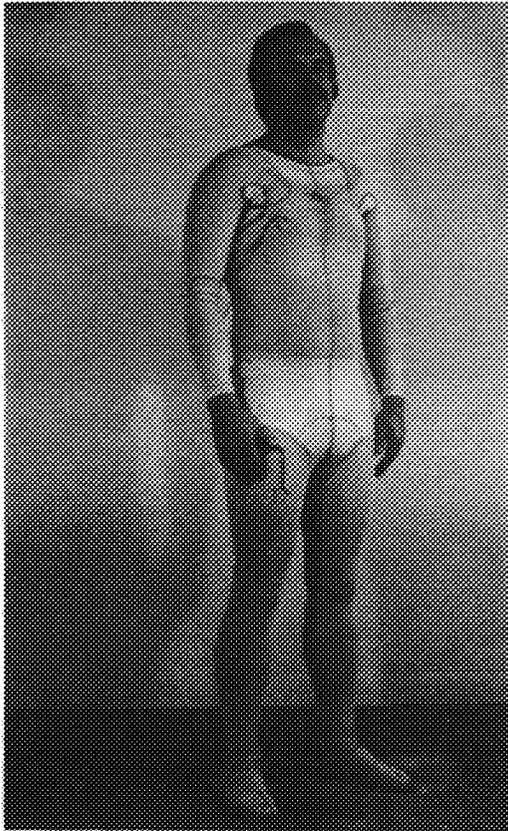
Figure 5. Slip layer (foundation garment) of light spandex power-net material; note padding outlines and bioinstrumentation patches. Subject C.
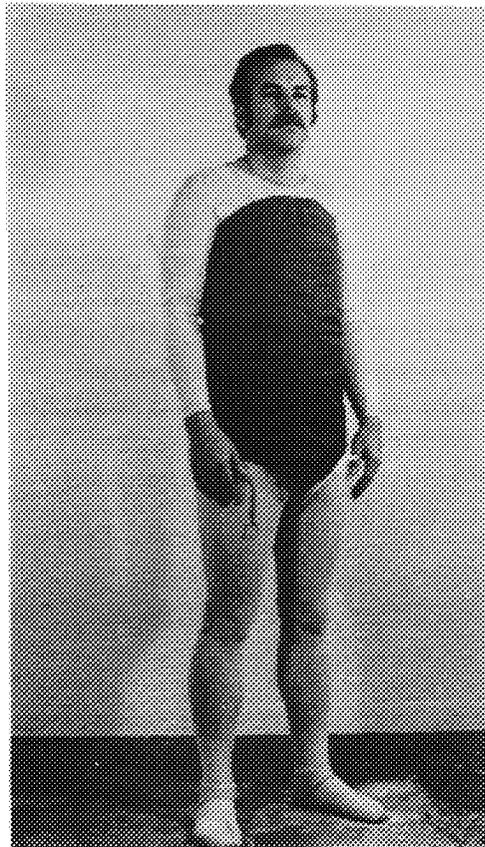
Figure 6. Subject C in slip layer showing positioning of torso pressurizing breathing bladder. Material is rubberized nylon fabric.

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Figure 7. Partial garment
of bobbinet fabric with lower
arm and leg segments removed;
bladder is normally positioned
under this garment, which is
used interchangeably with
garment shown in Figure 9.
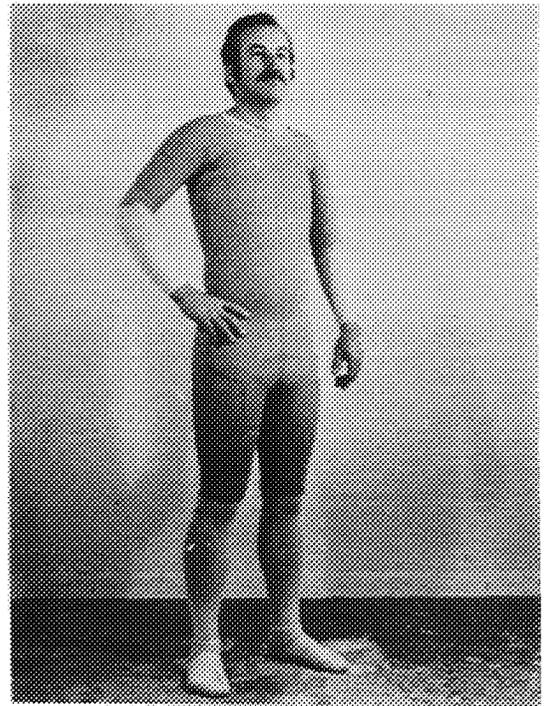
Figure 8. Power layer showing
hold-down straps attached to
baseplate for helmet. Powernet
fabric on torso and bobbinet
fabric on limbs. Torso modified
to reduce counterpressure.
Two such garments are used
with full suit.
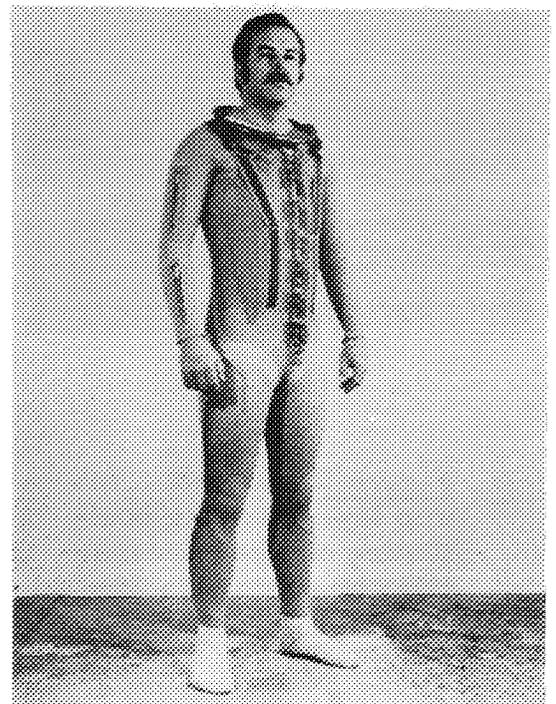
Figure 9. Full bobbinet garment
worn as intermediate layer.
Note dual limb zippers and
slit openings over joint
extensor surfaces.
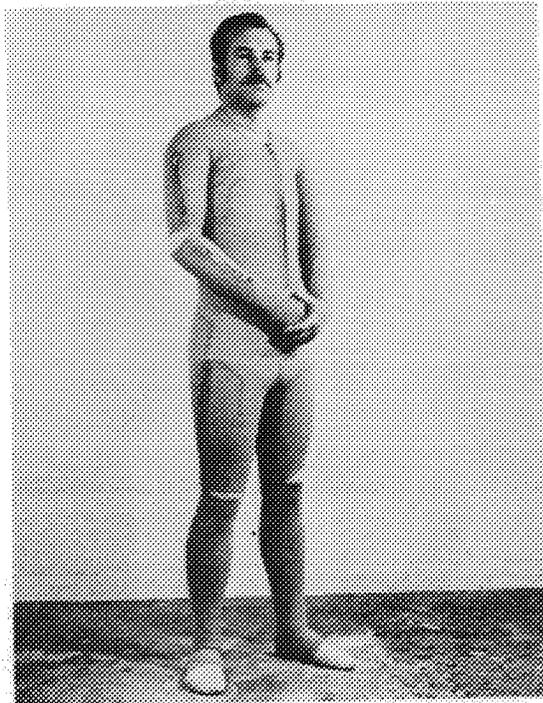
Figure 10. Appearance of
fully suited subject with full
bobbinet outer layer. Gloves,
footcovers, and helmet are
shown.   Backpack is not included.
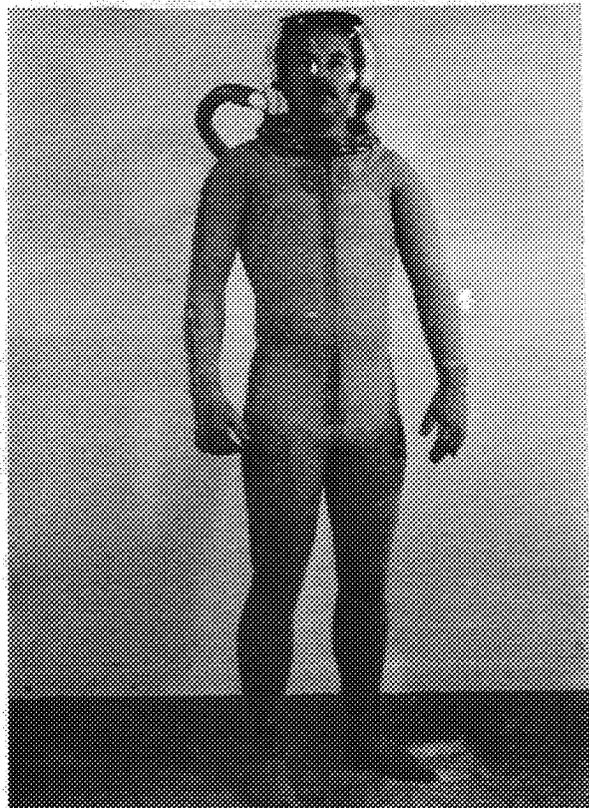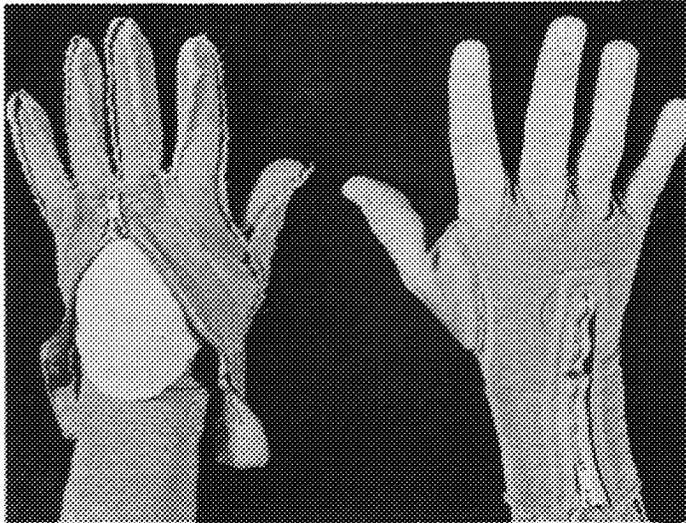
Figure 11. Gloves on left hand with gauntlet on right hand. Gauntlet is normally worn over glove. Note zippers on dorsum of hand, with simplify donning. Molded silicone rubber pad (white) is shown in position on left hand.
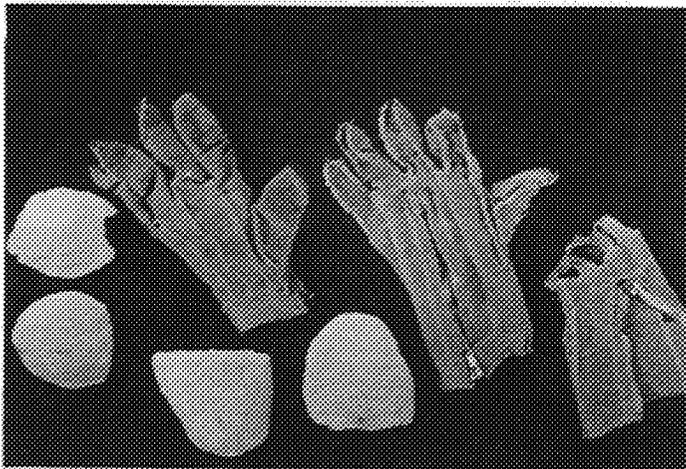
Figure 12. Two glove types (short and long wrist) and gauntlet, shown with rubber pads.
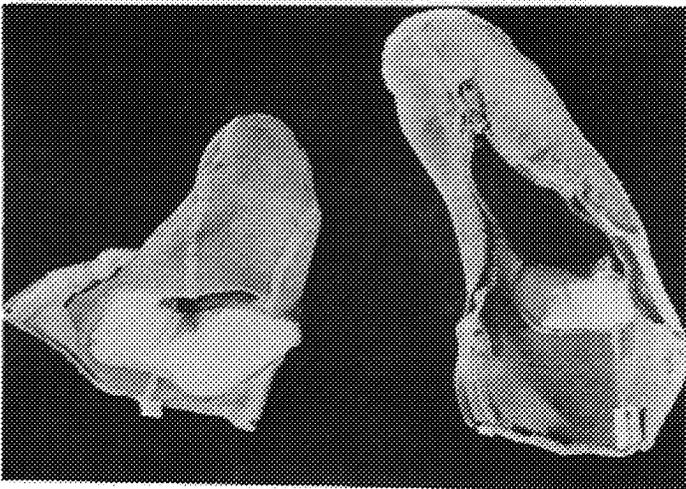
Figure 13. Foot covers (booties) fabricated of powernet material showing front zipper and interior padding. Right cover has been everted to show inner construction.

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SAS #10--The second test phase assembly. In preparation for the second test phase, modifications were made in existing garments to permit use of breathing pressures up to 200 mm Hg (3.9 psi) and to effect other improvements in the system. The 200 mm Hg breathing pressure design goal was adopted in order to increase the pO_2 safety margin during altitude tests at 80,000 ft equivalent pressures (21 mm Hg absolute). Garment changes made and their rationale include the following:

1. The amount of elastic fabric supplied counterpressure to the torso was further reduced by replacement of elastic fabric with non-stretch material (Nomex, see page 20) in previously existing layers. That is, pressurization of the torso was mainly provided by the breathing bladder. The purpose of this change was to reduce respiratory effort, lessen garment closure problems, and to limit bladder expansion.

2. Helmet restraint was improved by taking advantage of the non-stretch property of the Nomex fabric and by increased integration of the suit-helmet system.

3. Limb counterpressure was increased by removing material. This change was made to existing bobbinet garments selected from SAS #4 through #9 and was performed in accordance with need for higher breathing pressures.

4. Thigh and lower torso counterpressure was increased by altering power-net sections taken from SAS #2 to make a leg and girdle garment. Lab tests had indicated that the pelvis, hip, and thigh area may have been the site of blood pooling, and further elastic power was needed there.

The slip layer and three bobbinet layers used routinely as part of the SAS #10 assembly were essentially unchanged and taken from SAS #4 through #9. Selection of these layers was dependent upon the subject (B or C) under test, since individually tailored garments were available. Individually fabricated gloves, rounding pads, and foot covers from earlier garment series were also used. Basically, two hybrid layers, or layers consisting in part of sections from the earlier assemblies, were fabricated for use by both subjects tested in this assembly. Late in the project two pressurization girdles of the heavy powernet fabric were added to the assembly.

For convenience of description, we have arranged the basic assembly layers of SAS #10 in order of donning. Immediately over the light slip layer was positioned the torso pressurizing-breathing bladder assembly. The appearance of the subject at this stage in the dressing procedure is shown in Figure 14 (next page). Once the bladder assembly was in place the primary suit layer was donned. This garment consisted of bobbinet legs attached

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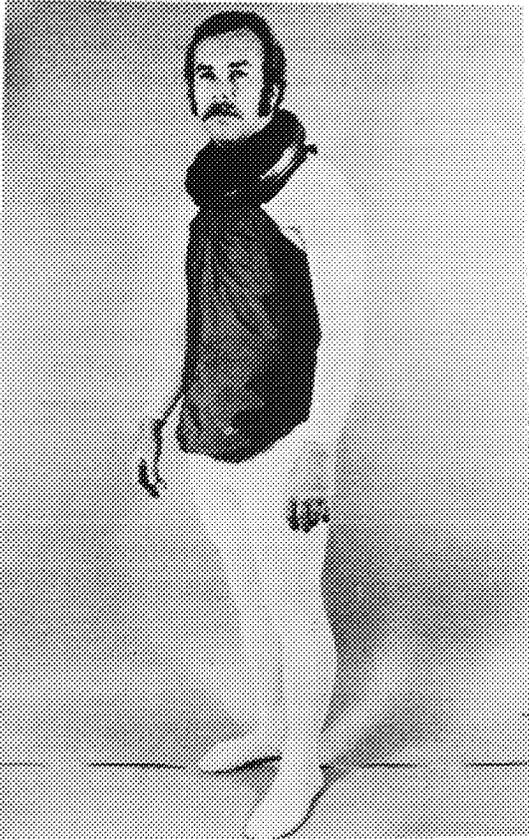
Figure 14. The appearance of the slip layer with the torso pressurizing breathing bladder in position. Note the attached neck seal and the bottom helmet seal ring assembly.

around the upper thighs to a custom fit torso section of non-stretch Nomex fabric. The split-ring collar-breastplate assembly was securely attached to the torso fabric at the proper level to capture the bottom helmet locking ring, neck seal dam, and bladder assembly. This garment served as the principal helmet "hold-down" in addition to restricting the amount of bladder expansion with helmet pressurization. The vertical and circumferential lengths of the Nomex fabric used were sized to the subjects to accomplish both of these tasks. Some adjustability in circumference around the chest was maintained through use of lace "take-ups" positioned lateral to the front midline entry zipper. Bilateral subaxillary zippers, and the anterior and posterior midline zippers, permitted the garment to be donned by bringing the attached split-collar breastplate assembly up over the shoulders to be secured into place on the bottom helmet locking ring. The leg counterpressure furnished by the bobbinet was adjusted to furnish a minimum of 25 mm Hg counterpressure over the largest thigh diameters. This was accomplished by sewing a tuck in the material, hence reducing the amount of cloth available for stretch. The amount removed was determined empirically by counterpressure measurements on the subjects. Arms were not pressurized by this garment, and the Nomex fabric was cut to fit around the scye line. The photograph of Figure 15 (next page) shows the appearance of this garment layer on one of the subjects. The helmet was usually donned and pressurized to 10-20 mm Hg immediately after this layer was in place.

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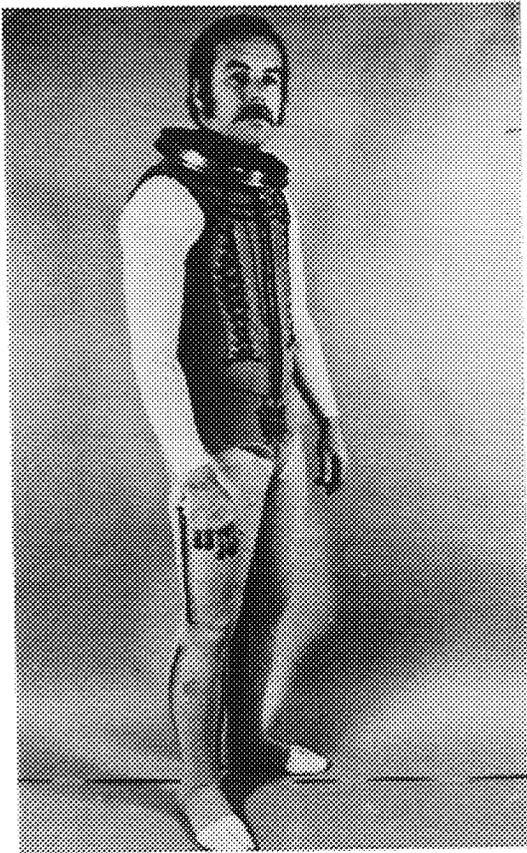
Figure 15. The main helmet and bladder restraint layer. The sleeveless garment has a torso section constructed of non-stretch Nomex fabric and leg sections of bobbinet fabric. The bottom seal ring is anchored by the split base-plate-breastplate assembly, which is attached firmly to the Nomex fabric.

The second hybrid layer was much like power garments from earlier series except that the powernet fabric over the torso area was replaced by Nomex. Both arms and legs were covered by bobbinet limb sections taken from an earlier garment and attached appropriately to the Nomex. This garment was designed to assist in the helmet hold-down function of the suit layers by fitting snugly down on the underlying breastplate assembly. Since helmet pressurization normally tended to pull the breastplate up off the shoulders, this force was reflected via the non-stretch torso fabric to the elastic leg sections of the garment much as in the previous layer. The two layers combine to furnish the major helmet restraint system. Subjectively, this method of helmet restraint was quite tolerable. Extreme pull on the crotch area did not develop, since the force was apparently distributed down the elastic fabric over the thigh area. A full length torso midline zipper allowed entry. The counterpressure furnished by the bobbinet limb sections was increased using the tuck and sew method described. The dual limb zippers were retained. This garment appeared as shown in Figure 16 (next page).

Outer layers used as part of the SAS #10 assembly were taken intact from SAS #4 through #9. Only garments made exclusively of bobbinet were used. Generally in the full pressure assembly three such layers were used.

Figure 16. The second restraint layer is a full body garment with a torso section of Nomex and limb sections of bobbinet.

The leg sections were removed from one of these garments, which was usually donned immediately after the first layer (which supplied leg counterpressure but not arm counterpressure) in order to maintain pressurization balance. These garments were also tightened on the limbs, particularly the legs, to take full advantage of the pressurization potential. These revised garments each supplied approximately 35 mm Hg counterpressure distally and 25 mm Hg proximally on the legs.

After laboratory tests revealed an apparent insufficiency in counterpressure on the upper thigh and lower abdomen when breathing pressures in excess of 140 mm Hg were used, two accessory girdle-like garments of the strong powernet fabric were added to the assembly. One of the girdles, shown in Figure 17 on next page, was rebuilt from the inner tape layers from two dual layer garments originally supplied with SAS #2 (see Appendix A). In its final form the girdle consisted of two matched sets of seven circumferential tapes which were pulled into position and closed on each lateral midline with Velcro. As can be seen in the photograph, the girdle extended from just above the knees to the level of the umbilicus on the abdomen. The amount of counterpressure supplied by this girdle was obviously variable; however, as much as 45 mm Hg over the upper thigh area was measured and found acceptable by the subjects tested. A minimum of approximately 25 mm Hg

Figure 17. A close-up view of the adjustable counterpressure girdle. This accessory was modified from an earlier powernet garment.
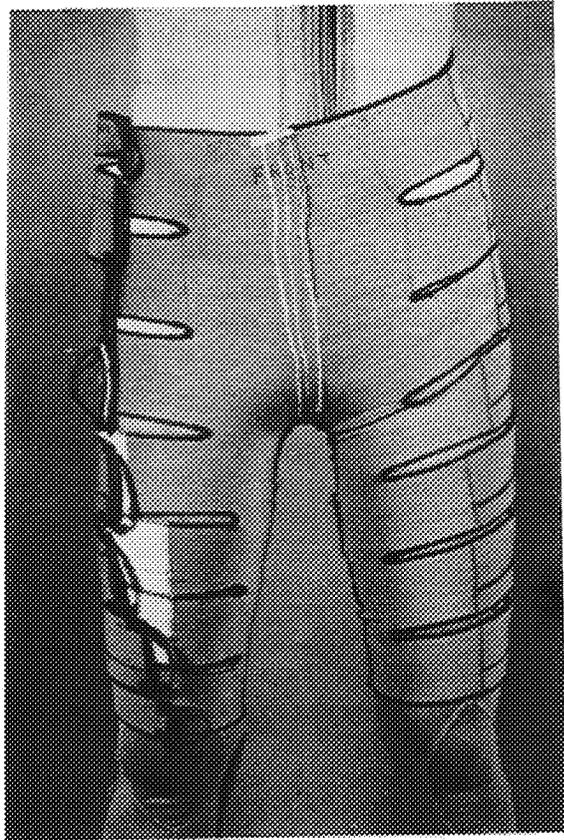
Figure 18. The second powernet girdle worn when breathing pressures in excess of 170 mm Hg were used.
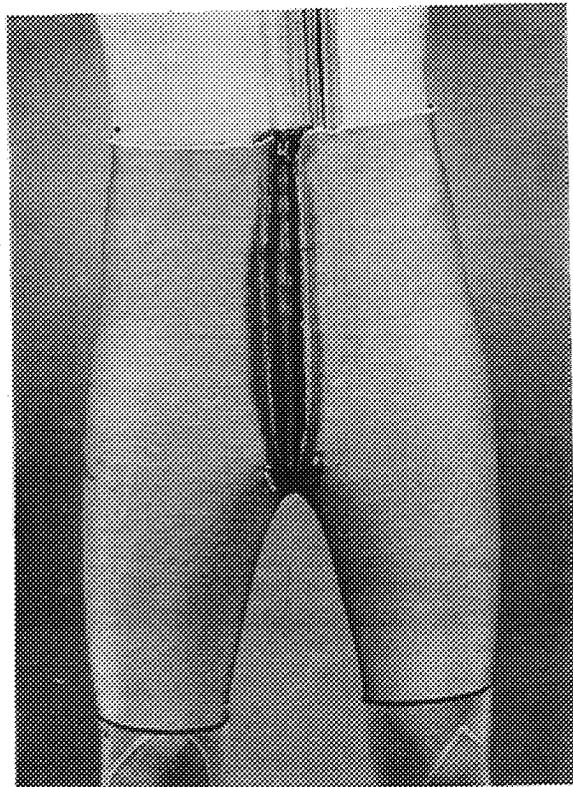
counterpressure was developed in the same area when the straps were pulled closed with just enough Velcro to hold. Pressurization over the abdominal area was less (about 15 mm Hg).

A second girdle, usually worn over the one described above, was also constructed of the powernet fabric and had a more conventional form, as can be seen in Figure 18 on page 33. This accessory was constructed by cutting down a full body garment originally fabricated with SAS #2. Body coverage was the same as the tape girdle. A single front midline zipper extending from the crotch to the top edge made donning easier. Approximately 25 mm Hg counterpressure was applied on the thighs, diminishing to less than 15 mm Hg at the upper border. These two girdle accessories combined to improve the pressure transition between that applied on the lower legs and that supplied by the torso bladder to the chest area. The weight of the assembly was 4.65 kg. Figure 19, below, shows a subject in the complete assembly (except for girdles) walking on a treadmill during a laboratory test.

Figure 19. The fully suited subject (except for girdles) shown walking on a treadmill during a laboratory test.

Positive Pressure Breathing System

A special closed circuit positive pressure breathing system was conceived and specified by Webb Associates; final design and fabrication was by L. J. Engineering Company, Westminster, California. The system was housed in an insulated fiberglas backpack, two views of which are shown below.
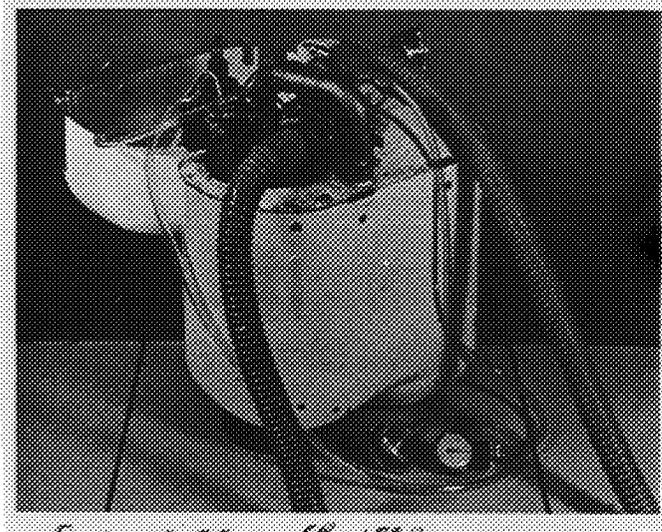
Figure 20. Three-quarter front view of the PPBS with the lid open to expose the accessible hardware.
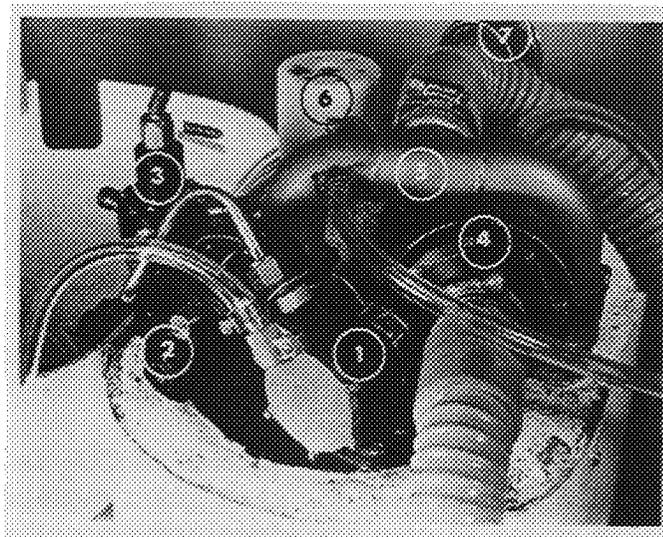
Figure 21. Close-up view showing the arrangement of the exposed PPBS components, as follows:
1) pressure regulator assembly
2) digital oxygen metering device
3) reservoir and pressure regulating vent
4) circulating motor-blower
5) breathing loop by-pass
6) filling port cap and relief valve
7) lox tank pressure gage

Sufficient expendables were supplied for four hours of continuous operation at an oxygen consumption ($\dot{V}_{O_2}$) of 1.5 lpm (work load of 450 kcal/hr). General descriptive information is as follows:

Total weight: charged	17.9 kg	39.5 lbs
uncharged	11.7 kg	25.7 lbs

Weight of expendables:

liquid O_2	3.0 kg	6.6 lbs
CO_2 absorbent	1.8 kg	4.0 lbs

Volume of expendables:

liquid O_2	2.6 liters	158 in^3
CO_2 absorbent	2.2 liters	133 in.^{3}

Pack dimensions:

total height	48.5 cm	19.1 in.
width	39.0 cm	15.4 in.
depth	24.0 cm	9.5 in.
lid height	14.0 cm	5.5 in.

Operation time	4 hours nominal (360 liters V_{O_2})

Operating pressure:

supply system	3260 mm Hg (gage)	63 psig
breathing loop	40-260 mm Hg (gage)	.7-5.0 psig

External power requirements: (circulating blower only)	115 volts, 400 cycle, 3 phase, at approximately 15 watts
O_2 source	liquid oxygen (lox)
CO_2 absorbent type	sodalime (Sodasorb^R), or Baralyme^R

To assist the reader in understanding the system operation, a diagram (Figure 22) is provided on the following page which shows the arrangement of the various components. Also shown is the relationship of the helmet and breathing loop to the supply system. The upper left portion of the diagram includes the lox storage tank, CO_2 scrubber, and a gas reservoir. These components, shown in Figure 23, were buried in the rigid urethane foam insulation which fills the pack.

Chemical absorption of CO_2 is exothermic, producing approximately 13.5 kcal of heat for each gram molecular weight (22.4 liters) of gas absorbed. In order to cool the circulating breathing volume coming out of the CO_2 scrubber, a heat exchanger coil containing cold oxygen surrounded the cannister. A portion of the flow was returned back around the lox supply tank to increase the gaseous phase conversion rate. The purpose was to supply greater quantities of cold O_2 to the heat exchanger at the expense of faster conversion
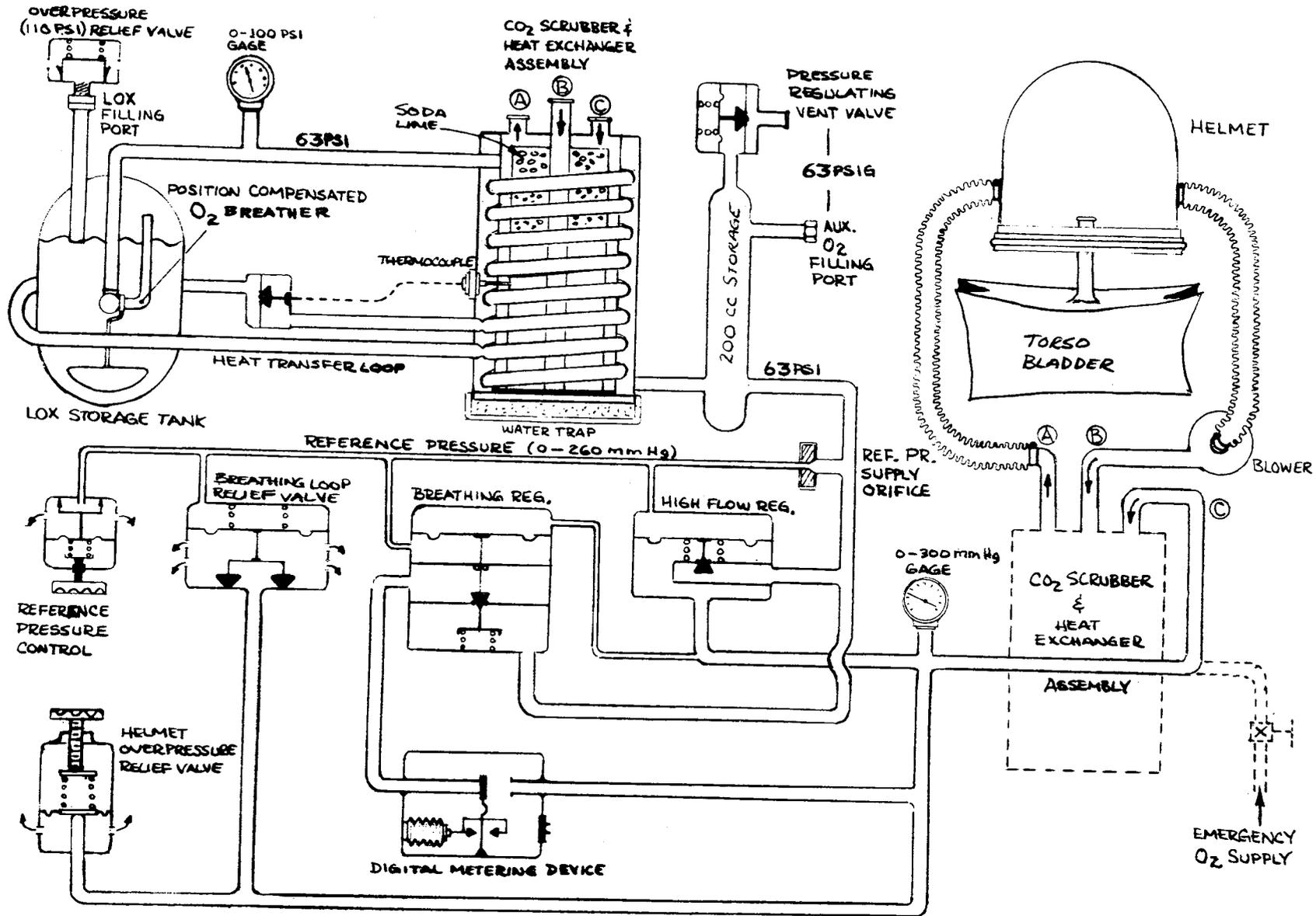
Figure 22. Positive Pressure Breathing System (PPBS) component diagram.

and boil-off. This loop included a thermal sensor and valve arrangement which automatically adjusted the volume flow rate in the feedback loop in attempting to maintain the circulating O_2 at the temperature set-point.
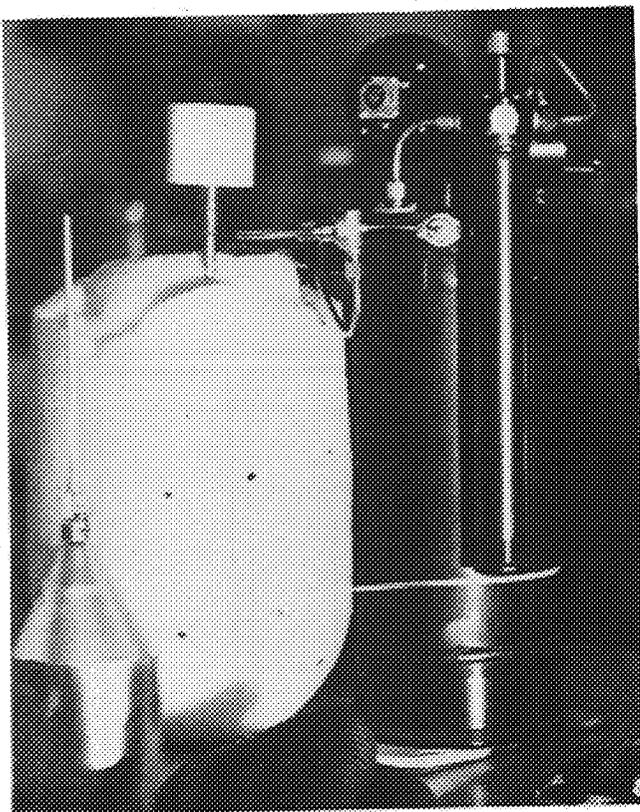
Figure 23. Assembled PPBS components as they appeared prior to insertion into the pack container.

The next component in the make-up gas supply line was a 200 cc gas reservoir. This acted as a ballast tank so that when the regulators supplying the breathing loop called for gas, the 63 psi lines were not abruptly depleted causing a major pressure reduction. The 63 psi regulating vent valve and a quick disconnect fitting for an external (auxillary) O_2 supply line were attached to the exposed portion of the reservoir cylinder.

The regulator package included a mechanically adjustable controller for reference pressure, a constant bleed device which loaded the reference lines ("dome system") of the regulators. A 100 cc/min orifice limited the flow into the line. This flow was later reduced to 75 cc/min. Small and remote, the manual reference pressure controller was hand-held by the subject in a position convenient for operation. The control knob was supplied with two detents to assist in selection of the 100 mm Hg and 170 mm Hg operational breathing pressures. When lowering the breathing pressure, the excess gas over the new set point was bled off through the breathing loop relief valve. Any increase in system pressure greater than 4 mm Hg above the control set point was dumped via this valve.

Liquid oxygen was selected for use in the system because of its compact nature and because it could provide cooling for the breathing loop. A closed circuit breathing loop with CO_2 absorption will become uncomfortably warm in a few minutes unless some cooling device is provided. The stainless steel lox tank contained sufficient stores to produce potentially more than 2200 liters of gaseous O_2. The screw cap for the filling port line included a 110 psig relief valve, in case a failure of the 63 psig regulating vent valve should occur. All gaseous O_2 produced in excess of that needed to maintain the 63 psig working pressure was boiled off into the environment via the vent valve. One of the special features of the system was the position compensated O_2 breather located in the lox tank. This device prevented liquid spillover into the breathing system regardless of pack positioning. The 3-degree-of-freedom weight (pendulum) oriented the breather above the liquid level in the converter. A 0-100 psi gage was supplied for visual indication of tank pressure.

The lox storage tank was originally charged by open pouring from a 10-liter dewar; however, prior to the second test phase a closed low-pressure transfer system was fabricated. A sketch of the system is given in Figure 24, and a photograph is provided in Figure 25 to show the arrangement during
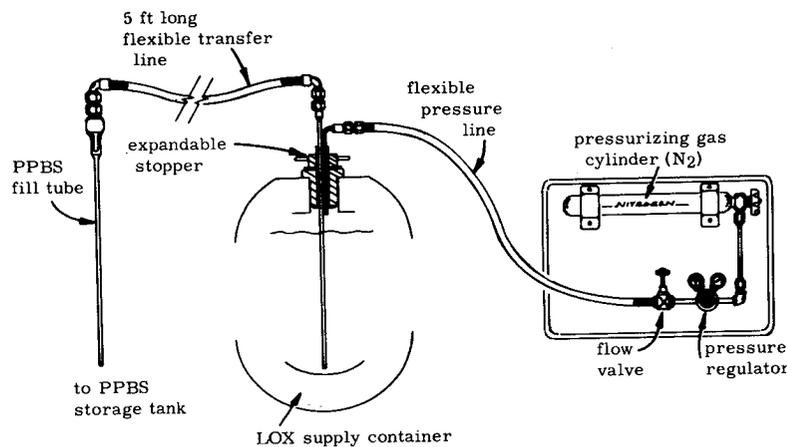
Figure 24. Diagram of the low pressure, semi-closed liquid oxygen transfer system.

operation. Except for the expandable neoprene rubber stopper for the dewar mouth, the entire device was constructed of 204 stainless steel and all permanent connections were brazed. Nitrogen was generally used as the driving gas. When pressurized to approximately 260 mm Hg (5 psig), the lox storage tank in the PPBS could be charged in six minutes. Not only was the method of filling considered more safe, but also the time required for the filling was reduced to one-quarter that needed for the open pouring method.
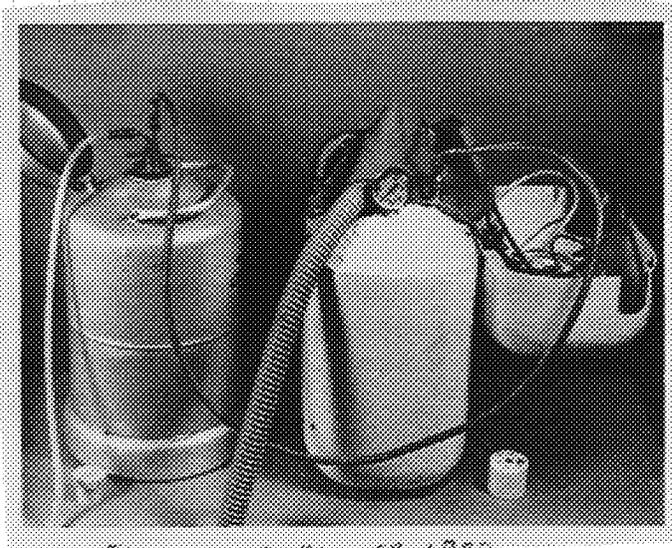
Figure 25. Arrangement of the liquid oxygen transfer system while charging the PPBS. Pressurization source is not shown.

Carbon dioxide was removed from the loop by soda lime (Sodasorb; Dewey and Almy) or Baralyme (Chemetron Corp.) contained in a scrubber cannister. Sufficient absorbent was provided to accommodate an estimated 350 liters of CO_2. An annular bed-radial flow cannister design was selected for maximum absorbent efficiency and its low resistance to flow. Soda lime and Baralyme, although less efficient than LiOH, were selected for use because of their established ability to function in the presence of water without a large increase in pressure drop and their low dusting properties. Measurements of CO_2 sampled in the breathing loop showed a maximum of 0.5% CO_2 after two hours of operation. Since water build-up in the absorbent bed can both increase resistance to flow and decrease absorption, a water trap was provided in the bottom lid of the scrubber housing. A moistened pad of foam urethane assisted in trapping the respired water in the sump and prevented the entrance of caustic solution into the breathing loop. As much as 225 gm (0.5 lb) of recoverable water has accumulated after two hours of use. The lid was accessible from the bottom of the pack and was removed for servicing the absorbent cannister and the water trap.

All make-up O_2 had to enter the breathing loop through either the breathing regulator or the high flow regulator. The high flow regulator was a safety device which supplied O_2 to the breathing loop at the set pressure and flows up to 170 lpm (6 cfm). When leaks (or oxygen consumption) exceeded 4.6 lpm, or when a sudden pressure drop of more than 3 mm Hg occurred, this regulator automatically cut in and the main breathing regulator system was by-passed. Because of the relatively large dome volume in this regulator, a six-second delay occurred at 1 ata ambient pressure. The lag was shortened considerably when the system was operated at reduced pressure (altitude). The built-in delay prevented spurious cut-in during normal operation. During rapid descents in altitude the regulator assisted in maintaining reasonably constant breathing loop pressures. During high flow operation, the main breathing regulator was deactivated via a feedback line to the dome system of the breathing regulator.

In normal operation make-up O_2 was supplied only through the breathing regulator. The O_2 was metered directly into the breathing loop through a fixed volume chamber which delivered 100 cc STP increments. This special component, which we have called the digital O_2 metering device (DOMD), permitted on-line monitoring of the subject's oxygen consumption ($\dot{V}_{O_2}$). A sketch showing some details of this device is given in Figure 26.
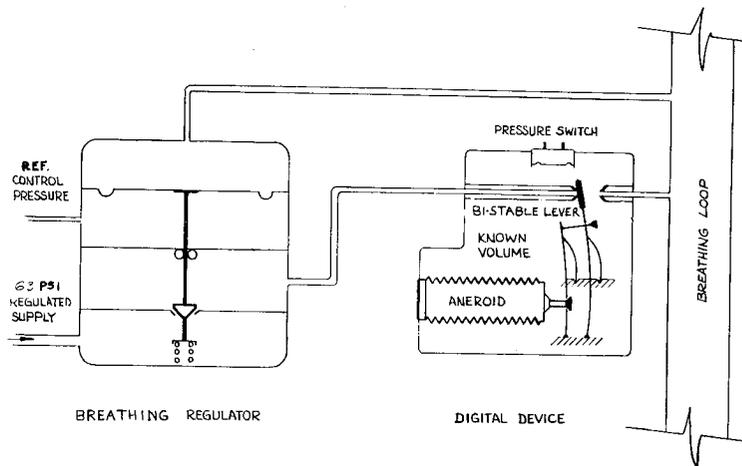
Figure 26. Diagram showing the basic components of the digital oxygen metering device (DOMD).

An aneroid operated bi-stable lever opened the chamber to the 63 psig supply via the breathing regulator. When the breathing loop pressure decreased to the set point, approximately 1 mm Hg below reference pressure, the device opened to the breathing loop side and an injection occurred. The expanded

volume from the chamber to the loop was 100 cc STP. While the chamber emptied in the loop, the bi-stable lever was snapped over to shut off the high pressure inflow. The chamber continued to fill and empty until loop pressure was re-established. By direct measurements with a gasometer, the injected increments were accurate to less than 5% error at all operational pressures. The DOMD was equipped with a pressure switch which allowed recording each injection as an event mark on a recorder. Quantification of injections gave us the $\dot{V}_{O2}$ of the subject. True, any accurate quantification of $\dot{V}_{O2}$ must preclude leaks from the breathing loop; however leak rates were established by having the subject hold his breath. The regulator assembly weighed 1 lb and measured approximately 12 x 8 x 7 cm. Two photographs showing the entire regulator package including the DOMD are given in Figure 27.
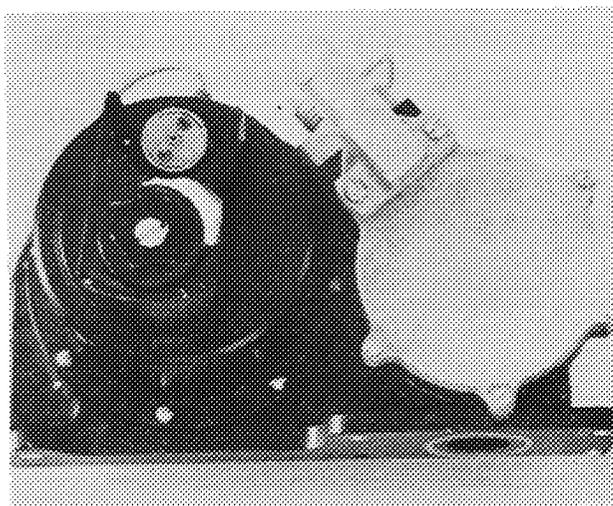
Figure 27. Top and side view of the PPBS regulator assembly.
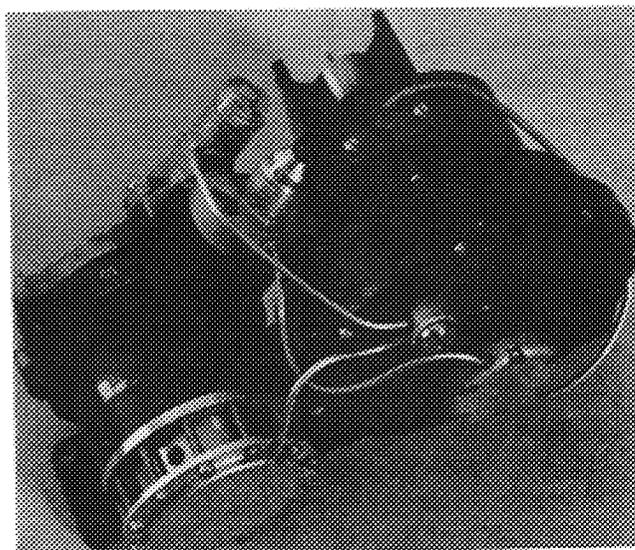
The only remaining component of the PPBS assembly to be described is the motor-blower. This special squirrel-cage, centrifugal type blower discharged the helmet effluent directly into the CO_2 scrubber assembly and overcame any breathing resistance the system might otherwise have produced. Because of the recirculating blower, no directional valves were needed in the breathing loop. The motor–blower (Globe Industries Division of TRW, Inc.) is a duplicate of a type developed under a NASA contract. The device is traceable to the Apollo project contract with North American Aviation Division of North American-Rockwell Corporation, and has the control number NE901-0030. The AC motor was powered by 115 volt, 400 cycle, 3-phase current; it consumed 16 watts and was sealed for O_2 service. A rectifier-inverter power supply was fabricated so that ordinary 115 volt 60 cycle power could be used. The power supply was housed in a separate cabinet and connected to the PPBS via a 20' cable to allow the subject freedom to move about.

The selected operational breathing loop flow rate was 175 lpm (6.2 cfm), at which rate the system pressure drop was 0.75 cm H_2O (0.3 in. H_2O). The low pressure drop was achieved by various design details, including use of 3.2 cm (1-1/4 in.) ID lines on the helmet loop, the radial flow CO_2 absorber bed, and so forth. At full power the blower was capable of delivering in excess of 370 lpm (13 cfm) at a 3.8 cm H_2O (1.5 in.) system pressure drop. The motor-blower weighed 500 gm (1.1 lbs) and had maximum dimensions of 12.4 cm (4.9 in.) width by 8.4 cm (3.3 in.) height, including fittings and connectors. A top view of the motor-blower is presented in Figure 28.
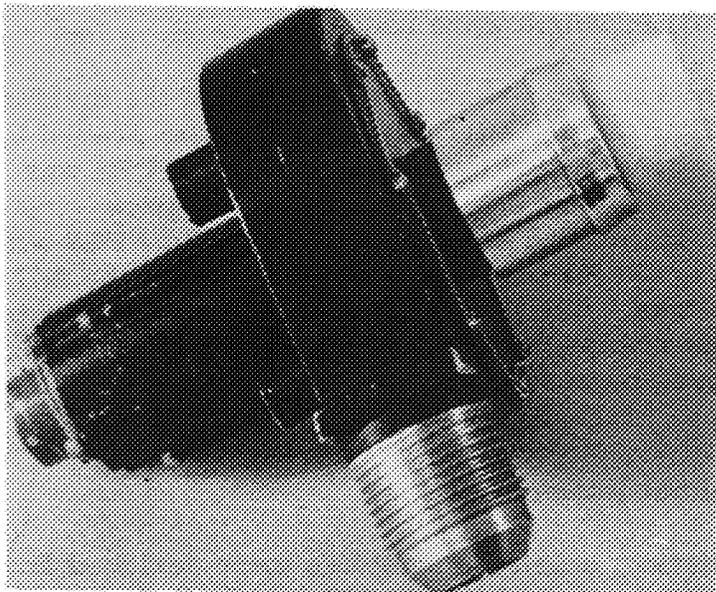
Figure 28. Top view of the PPBS motor-blower, which circulated the oxygen in the breathing loop.

Since the breathing system was mechanically set to operate at a fixed differential compared to the ambient pressure, as the system was taken to altitude the excess O_2 bled from the system via the breathing loop relief

regulator. In descents, set point pressure requirements not met by the DOMD were served after a short delay by the high flow regulator. Late in the project a secondary bleed valve was incorporated into the helmet loop. This device was pre-set to 233 mm Hg (4.5 psig) to prevent loop overpressurization for any reason, e. g. failure of reference controller or primary relief regulator. During the second phase altitude tests, an additional safety feature was installed into the PPBS. In the event of a total PPBS failure, emergency O_2 was supplied to the helmet loop from an O_2 cylinder housed in the altitude chamber. Designed strictly as a "get-me-down" back-up, oxygen was deliverable to the subject via a two-stage regulator by operation of manual valves. Valves were positioned conveniently inside and outside the chamber so that either the test subject or an observer could easily operate them. This system was selected in preference to complex PPBS alterations or electrically operated devices because of its simple "fail safe" nature.

Oxygen in the breathing loop at the selected pressure was delivered to the helmet via 3.2 cm (1-1/4 in.) ID flexible plastic hose. An initial hose of urethane formed on a spring steel wire coil was replaced early in the project by a similar variety in which the plastic material was polyvinyl chloride(PVC). Hoses were provided with end pieces sized to slip fit snuggly on the helmet O_2 ports and PPBS fittings. Adjustable stainless steel hose clamps were used to secure the hoses and to prevent leaks. Prior to use these hoses were pressure tested to 520 mm Hg (10 psig) and outgassed for eight hours at 70°C. Two lengths of hose were used. The longer, measuring 1.8 m (6 ft) in length, were used when the PPBS was not carried by the subject. In this case the PPBS was held by a specially constructed support chair. The subject was allowed a reasonable degree of freedom. When the PPBS was worn by the subject, shorter hoses 0.9 m (3 ft) in length were used.

Because of the lack of anthropomorphism in the design of the molded fiberglas backpack, the originally provided carrying strap system proved to be unsatisfactory. Therefore, when carried by the subject, the PPBS was mounted upon a separate commercially purchased mountain type pack carrier rig (Himalayan Pak Co., Inc.) Both subjects who wore the PPBS with this device reported that the 18 kg (40 lb) load was not noticeable in the fully suited and pressurized configuration. The natural tendency of the garments to pull the shoulders forward was counterbalanced by the weight of the PPBS, which was shifted to the lower back by the carrier assembly.

Helmet Assemblies

During the project two distinct helmet assemblies were designed and fabricated for use. Both helmets were basically the full bubble or fishbowl type, and both included the necessary accessories for integration into the

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SAS system. Following specifications developed by Webb Associates, the original helmet was constructed by Protection, Inc., Pomona, California. Early tests led to rather extensive modifications in this assembly, resulting in a modified helmet which was used in most of the suit trials during the first test phase of the project. For the sake of clarity, this helmet in its later form will be called the modified helmet. Because of extensive usage and the resulting wear, this helmet was replaced by a more sturdy version which was used in the second test phase. This, the final helmet, was designed and assembled primarily in our laboratory. Several components from the original helmet were retained; however, a new bubble was used and new interconnecting rings were fabricated. Construction of the various rings was performed by Tech Development, Inc., Dayton, Ohio.

The original and modified helmet assembly.--The original helmet assembly, as delivered, consisted of the following basic parts: the fishbowl helmet; a custom molded full head seal and neck dam with an attached anti-rise extension on the crown; a split ring locking baseplate and breastplate assembly; and the required interconnecting rings and seals. A diagrammatic presentation of this assembly is given on the following page in Figure 30, and a photograph of the completed helmet is given below (Figure 29).
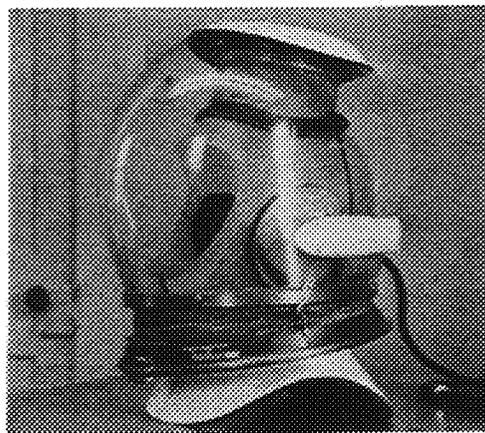
Figure 29. The original helmet assembly including the split ring locking baseplate and breastplate.

Rotating seal retaining ring
assembly (fiberglas and
aluminum)

Rotating seal
(anodized aluminum,
nylon and rubber)

Stack sleeve retainer
(fiberglas)

Bellow restraint
cable (stainless
steel)

Helmet seal ring
(anodized aluminum
and rubber seal)

Helmet seal ring
locks (2) -- (stain-
less steel)

Shoulderpiece
(fiberglas)

Foam padding

Helmet
(clear polycarbonate)

Oxygen connections
(aluminum)

Stack sleeve
(rubberized cloth)

Helmet-bellow seal ring
(anodized aluminum)

Neck bellows
(rubberized cloth)

Ear phones and
microphone
(aircraft type)

Head seal
(natural rubber)

Head seal ring
(anodized aluminum)

Split ring neck collar
(anodized aluminum
with stainless
steel hinge
and lock)

Figure 30. Line drawing of the original helmet assembly showing components;
front view.

The bubble (generously supplied by Airlock, Inc., Milford, Conn.) was formed of clear polycarbonate. Two lateral ports measuring 3.2 cm (1-1/4 in.) ID were attached for connecting the breathing hoses from the PPBS. A bellows made of rubberized nylon cloth was attached to the bubble mounting ring. Laterally positioned flexible steel cables restrained the bellows (5 cm height), allowing 15° of forward-aft nodding motion. An opening at the top of the bubble was equipped with a fitting to accept a rotating seal ring which measured 14 cm (5-1/2 in.) in diameter. This rotating ring, which was modified from the arm seal of a pressure suit, was attached via a rubberized nylon cylinder to a molded fiberglas base cemented onto the rubber head seal. The purpose of this device was to negate helmet rise by equalization of internal force vectors. This anti-rise design, similar to that frequently used in partial pressure suit helmets, leaves an area over the crown of the head unpressurized. To avoid rise, the unpressurized area must equal the cross-sectional area of the subject's neck. Without this device and at the operational pressure of 170 mm Hg, the estimated net rising force would equal nearly 30 kg. Conventional restraint harnesses are uncomfortable and limit trunk mobility; hence they were considered to be non-compatible with the SAS concept. The rotating seal did allow approximately 100° of turning arc. Turning further caused leaks around the face opening of the head seal. Motion in the saggital plane was restricted to that available from the main bellows (see above).

The head seals and neck dams were molded in a single piece and attached directly to the bottom locking seal ring. Since a good seal was imperative, head and shoulder plaster casts were made of each of the subjects for use in custom dip molding of the gum rubber seals. The primary seal surface was around the cut-out for the face. Molded ear cups from a headset and a boom microphone were secured in the appropriate positions directly to the rubber seal. The tubular boom microphone (Model MS 50/T55, Pacific Plantronics, Santa Cruz, Calif.) and the headset were generally operated using available compatible amplifier systems. A portable solid state amplifier and speaker were fabricated for use in remote test situations. When donned, the bottom locking seal ring of the head seal-neck dam was held in place by the baseplate. The aluminum baseplate and the attached fiberglas shoulder support (breastplate) were split with a hinge in the rear to allow entry. A stainless steel snap lock in the front held the assembly closed. For comfort and fit, the shoulder supports were also custom molded from casts made of the subject's shoulder area. A thin, 0.5 cm (1/4 in.) pad of open cell urethane foam lined the support. In addition to serving as an anchor for the bubble, the breastplate served to maintain proper helmet orientation with movement.

Considerable effort was put forth to make the helmet not only a functional device but also comfortable. In addition to the plaster casts made

for forming the rubber seals and breastplates, a number of anthropometric measurements from the head and shoulders of each subject were taken. To insure proper sizing, the components were positioned using the plaster casts of the subject's head and shoulders. In the photograph below (Figure 31), taken during the construction phase, the various parts are shown in one of several configurations studied.
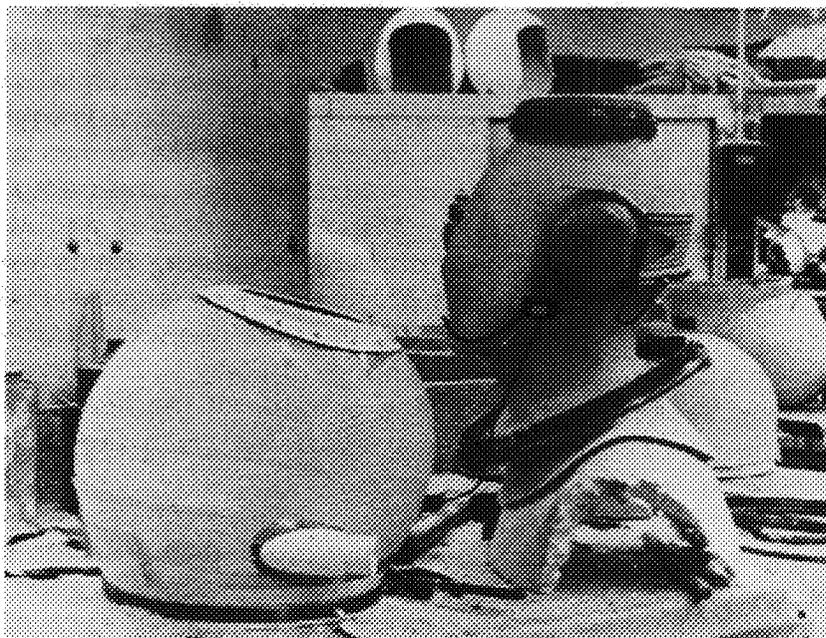
Figure 31. Some components of the original helmet as they appeared during construction.

Actual tests with this helmet demonstrated the anti-rise feature to be present; however, several problems were evident. The head seal became uncomfortable after a period of time; a good seal was difficult to obtain with movement and increased helmet pressure; the upper rotating seal leaked; and the range of head movement, although reasonably within the specifications, was limited. For these reasons it was concluded that some changes were needed if a functional test helmet were to result.

During some early tests it had been discovered that the SAS garments themselves possessed sufficient restraining power, if directly attached to the helmet, to keep the helmet rise within acceptable limits. By placing the fiberglas breastplate under a powernet garment, it was discovered that we could pick a 70 kg subject off the floor by the locked baseplate. A displacement of only approximately 0.5 in. of the breastplate off the shoulders resulted. Since at least two such powernet garments would be needed in the full suit, and

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since 70 kg is more than twice the force to be restrained at 170 mm Hg helmet pressure, a garment hold-down appeared feasible. The anti-rise helmet had originally been specified because of the desire to avoid the motion limiting and uncomfortable conventional restraint harness. Our fears that the suit restraint might produce similar effects were soon dispelled as the force distribution throughout the garment produced no detectable crotch pull. Some rise was obtained when the suited subject would sit; however, torso bending did not produce malalignment problems.

After a series of changes, the original helmet turned into the modified helmet shown in Figure 32 as a photograph and in Figure 33, next page, as a line drawing.

Figure 32. Side view of the modified helmet assembly.

Examination of these illustrations will show that the head seal, anti-rise bellows, and the main helmet bellows were eliminated. The original microphone was retained; however, the earphones which had been sealed to the rubber head seal were replaced by a light weight headset. Small open-cell plastic foam pads were provided to prevent blockage of the external auditory canal. The top opening in the bubble which accommodated the rotating seal assembly was simply closed off by a fitted aluminum plate. The main bellows was removed to correct leak problems; however, this change also lowered

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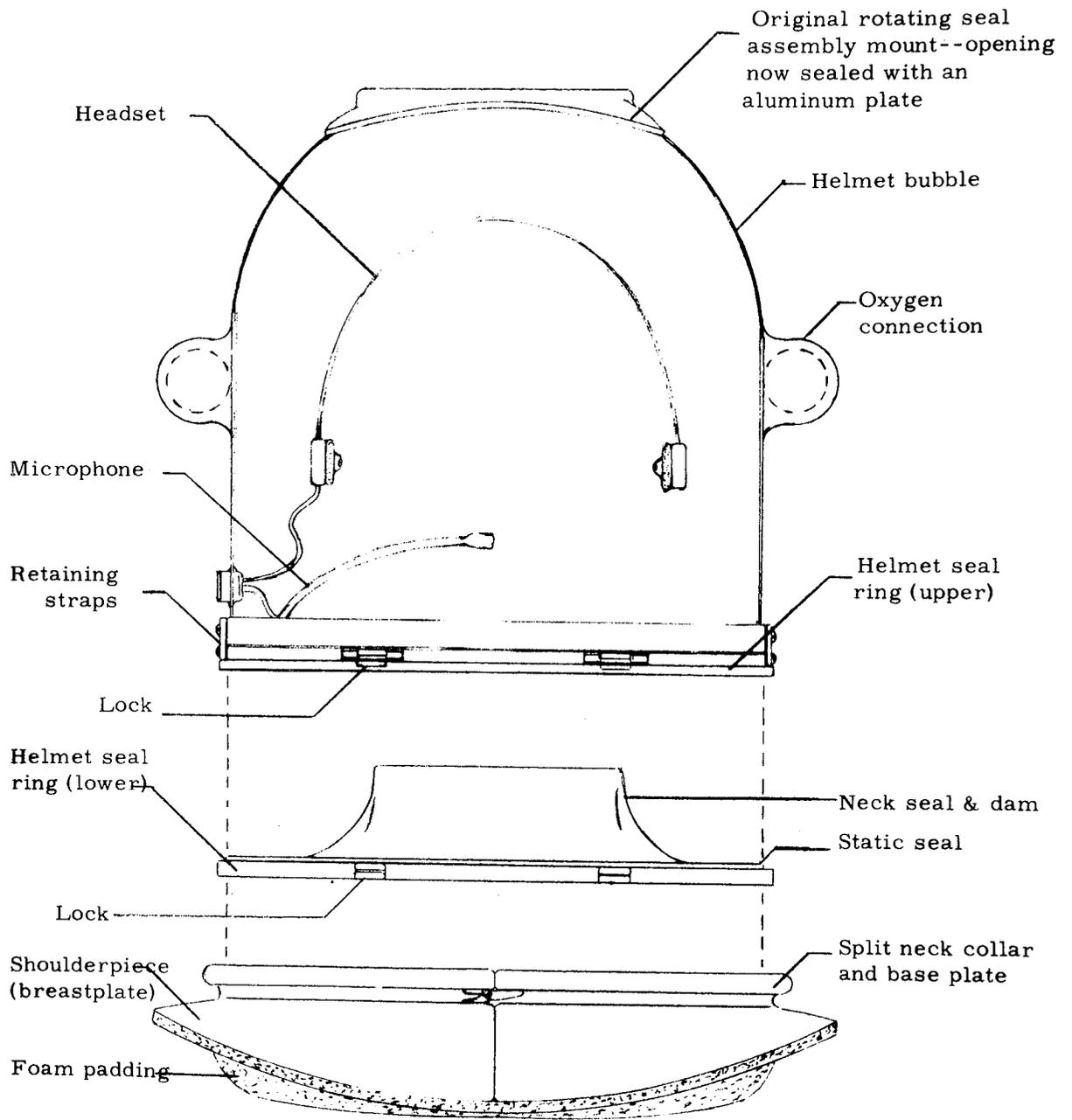
Figure 33. Line drawing of the modified helmet assembly.

Labels in the figure:
- Headset
- Original rotating seal assembly mount--opening now sealed with an aluminum plate
- Helmet bubble
- Oxygen connection
- Microphone
- Retaining straps
- Helmet seal ring (upper)
- Lock
- Helmet seal ring (lower)
- Neck seal & dam
- Static seal
- Lock
- Shoulderpiece (breastplate)
- Split neck collar and base plate
- Foam padding

the bubble in relation to the head, increasing the amount of allowable helmet rise. The original head seal and neck dam were replaced by a simple neck seal and dam arrangement. The neck seal and dam were dip molded of gum rubber by Trexler Rubber Co., Ravenna, Ohio. Plaster cast forms of the neck and upper shoulder area of each of the subjects were supplied by Webb Associates. The neck seals and dams were subsequently reinforced by cementing foam neoprene rubber 0.3 cm (1/8 in.) thick and gum rubber 0.6 cm (1/4 in.) thick to various portions of the seal. We hoped to decrease the amount of dam deformation with increasing pressure and generally improve wearer comfort. Although head movement in the bubble was now unlimited, some problems were apparent with the uneven application of pressure to the neck area. One additional modification which involved this helmet assembly was the direct coupling of the breathing bladder to the bubble via a connecting line through the neck dam portion of the seal. This line, which was limited in size to 0.95 cm (3/8 in.) ID, did result in a 2 cm (0.8 in.) H_2O pressure drop to move volumes in and out of the bladder; however, no additional load was added to the PPBS blower, since the bladder was T'd off the breathing loop. This arrangement improved the logistics of helmet donning by avoiding connect-disconnect problems with the breathing loop lines as garment layers were added.

The bladder was constructed of rubberized nylon cloth and covered much of the anterior portion of the torso (see Appendix A-3). A spacing material (Trilox^R--Uniroyal) lined the bladder to prevent pinching off areas and reducing the functional capacity. The volume of O_2 contained in the bladder was variable depending on the differential pressure between the breathing loop and that applied by the garment; however, during the later tests the method of use allowed for a maximum volume of approximately 8 liters O_2. Late in the test phase the bladder was used as a torso pressurization device. Since the applied pressure to the torso must equal the bladder (breathing loop) pressure, a better breathing balance was obtained. In addition, garment applied counterpressure was reduced, making donning easier.

Final helmet assembly. --In preparation for the second test phase, a new helmet was fabricated. Justification for this undertaking was based upon the desire to improve respiration by improving the neck seal and breathing bladder arrangement. Also, the modified original helmet showed wear, the leak rate was too high, and the helmet was considered unsafe for use at higher breathing pressures. As can be seen in Figure 34, the photograph below, and Figure 35, the drawing on the following page, this helmet was very similar in appearance to the original modified version. Several original component parts were re-used. Transferred parts included the intercom (microphone and headset), the breathing line ports, and the bottom seal ring locks.
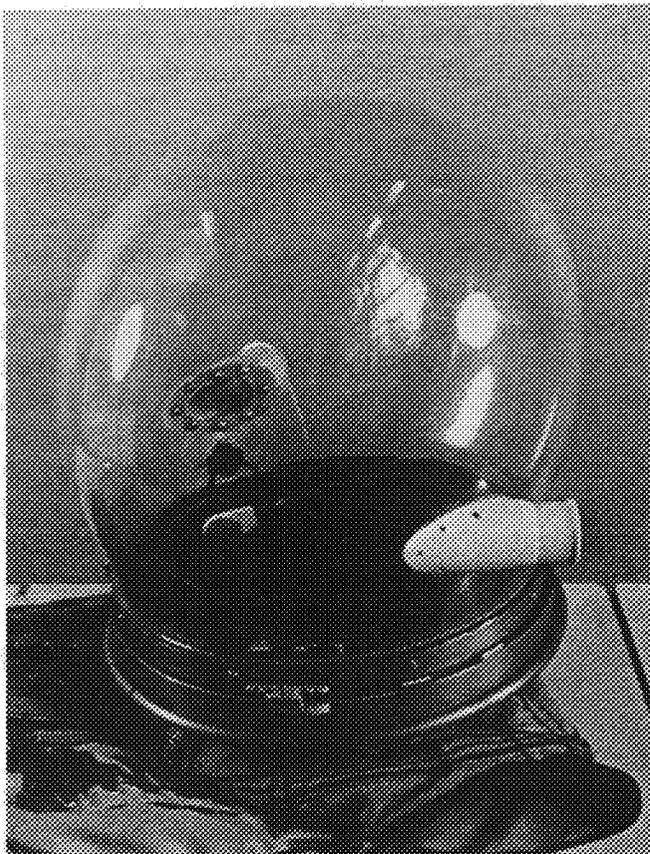
Figure 34. Photograph of the final helmet assembly.

A new polycarbonate bubble (also supplied by Airlock, Inc., Milford, Conn.) was used. Prior to installation the bubble was subjected to static pressure tests to 2 Ata. Also, new and more sturdy upper and lower seal rings were made. Both rings were machined from 2240 aluminum and anodized (blue) prior to assembly. Size of the upper seal ring was dictated by the diameter of the finished bubble. The neck dam seal ring, which was attached to the bottom surface of the lower ring, was sized to fit the inside diameter of the retaining groove in the split baseplate of the breastplate assembly when locked. The arrangement of the entire assembly as it would appear in cross-section is given in Figure 36, on page 54. As can be seen by examination of the figure, the main sealing function was performed by a quad ring seal of neoprene rubber (Minnesota Rubber Co., #Q4270). This seal was selected because of its dual sealing capabilities and because of the greater tolerances of rotation stress (imposed when the helmet was locked into place) than the delicate static seal used in the earlier helmet. Later it was learned that a proper sized "O" ring would also seal satisfactorily. The bubble was sealed in a 1.25 cm (0.5 in.) deep groove in the top of the upper ring with a moderately flexible epoxy plastic (Ecobond #45, Emerson-Cuming,

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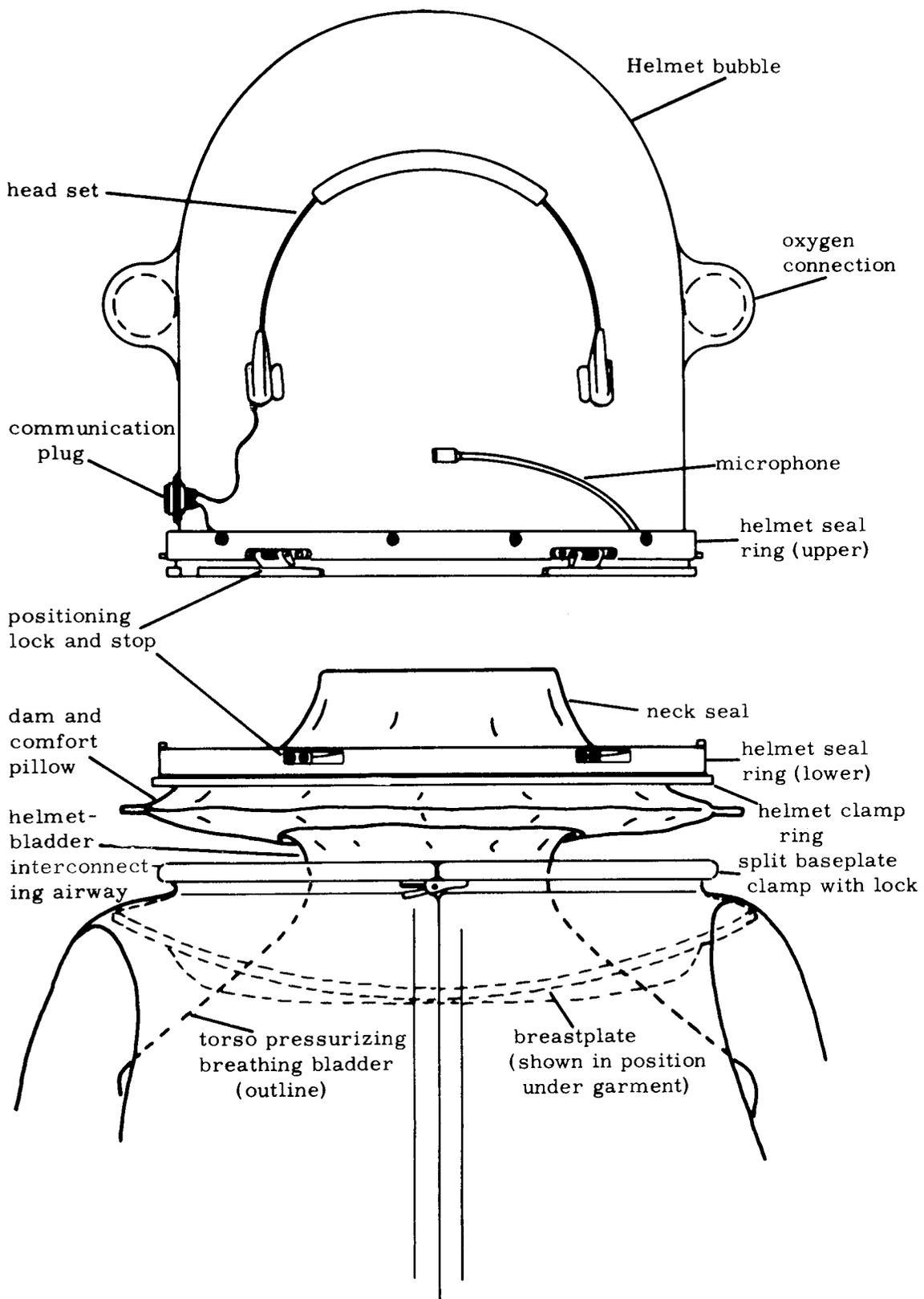
Figure 35. Line drawing of the final helmet assembly showing the neck and the interconnection to the torso pressurizing breathing bladder.

Inc.). To insure against separation, the bubble was additionally anchored by six 4-40 stainless steel screws placed equidistant around the periphery.
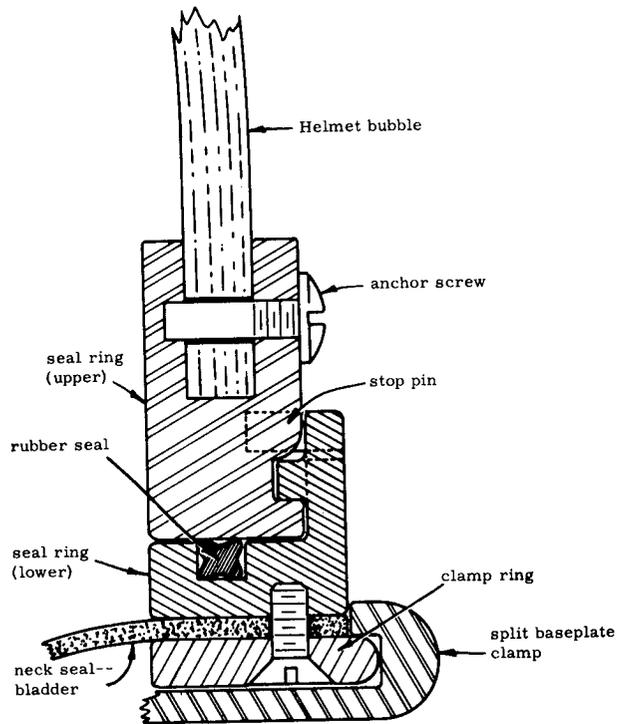
Figure 36. The final helmet ring assembly in cross-section.

Some general descriptive data for the completed assembly are the following:

Weight: bubble assembly -------------	1.2 kg	2.6 lbs
Volume: bubble ---------------------	12.8 liters	3.4 gal
Height, overall (bubble plus breastplate) ---	49.5 cm	19.5 in.
Height: bubble, maximum ------------	38.1 cm	15.0 in.
Length: bubble, maximum ------------	30.5 cm	12.0 in.
Width: bubble, maximum -------------	24.1 cm	9.5 in.

The integration of the torso pressurizing breathing bladder with the helmet is shown pictorially in Figure 37 (see also Figs. 14 and 35).
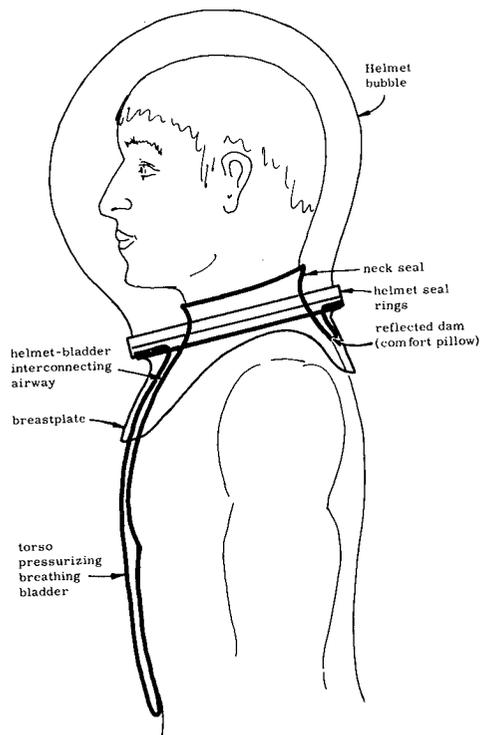
Figure 37. The interconnection of the helmet with the torso pressurizing breathing bladder. Bladder shown in cross-section only.

The neck seal and dam were captured on the periphery by a clamp ring secured to the under surface of the bottom helmet seal ring by 24 stainless steel screws (4-40) placed at 15° intervals. Immediately inside the clamp ring the seal is reflected to form a sort of pillow ring upon which the breastplate sat. Upon pressurization this pillow inflated to relieve some of the stress imposed on the shoulders by the pull of the helmet restraint garments on the breastplate assembly. On the front midline a tubular opening in the pillow extended down under the breastplate to connect with the torso bladder. The size of the airway (approximately 20 cm^2 when inflated) was large enough so that pressure drops associated with respiratory induced oxygen flows were negligible. Subjectively, this system was considered quite comfortable and the work of breathing was reduced; however, some effort was required to overcome inertia effects produced by contractive movements in the overlying elastic garment layers. The general shape of the torso pressurizing breathing bladder was similar to that given in Appendix A and shown in Figure 14. The final bladder used was actually a modified version of the one produced as part of the SAS #4 assembly.

The neck seal and dam were constructed of 0.3 cm (1/8 in.) thick nylo-prene, which consists of foam neoprene rubber (unicellular) backed with nylon fabric. The bladder material was rubberized (neoprene) nylon fabric. Several prototype bladders were constructed early in the second test phase of the nyloprene fabric. The bladder, neck seal, and all materials in intimate contact with the breathing loop oxygen were outgassed by exposure to a 70°C environment for eight hours prior to use. The bladder volume was limited to a maximum of approximately 6 liters by the restraint layers (Nomex fabric) of the final suit assembly.

METHODS

Test Program and Measurements

The test program cannot be entirely separated from the development process since the two overlapped in time and objectives. The overall organization centered around the following basic sequencing of events:

1. Development of specifications
2. Production of the item
3. Prototype testing individually
4. Revisions
5. Re-testing
6. Integration into the system
7. System testing--manned

We have discussed the evolution and have described the various components of the SAS system in the preceding sections of this report; therefore we are concerned here principally with the manned test program. For training and safety, bench performance testing of the life support components (PPBS and helmets) of the system were run prior to suited tests. Therefore, the test program concentrated on determining the effects of the total system upon the physiology and performance of the suited subjects.

The program consisted of a series of suit trials in the laboratory (1 atmosphere) followed by hypobaric tests in an altitude chamber. These events were repeated in a second round of testing, called the second phase tests. Starting in the first test phase with SAS assemblies designed to furnish 100 mm Hg counterpressure, we worked gradually toward suits which would maintain physiological balances in subjects breathing O_2 at pressures up to 170 mm Hg while at 80,000 feet --the altitude chamber test goal. During the second phase the pressurization goal was increased to 200 mm Hg breathing pressure in order to produce a greater margin of safety in the altitude chamber. The second test phase resulted largely from problems detected late in

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the initial laboratory test phase and during the first altitude chamber runs. The objectives during the second test phase were to improve system safety, comfort and integration capabilities, and to achieve the increase in the nominal operation pressure.

The four basic parts of the test program, their individual goals, and the number of experiments in which data were collected for each, are outlined below.

First Phase

a. Laboratory: physiological verification of SAS principle up to 170 mm Hg breathing pressure at 1 atmosphere ambient. 15 tests.

b. Altitude chamber: exposure of subjects in the 170 mm Hg assembly to ambient pressures of 20 mm Hg (80,000 ft equivalent). 5 tests.

Second Phase

a. Laboratory: general improvement of system and increase in nominal breathing pressure to 200 mm Hg. 15 tests.

b. Altitude chamber: re-exposure of subjects in new assembly to 80,000 ft equivalent. 3 tests.

Many additional tests of one sort or another were also performed in the course of the project. Since these tests were primarily for learning, often little hard data were collected. For example, as each new garment assembly was delivered, wear trials were conducted. During these trials we were primarily interested in determining problems related to donning, general fit, comfort, and learning how to integrate the various pieces of the suits and breathing devices. Findings from assembly trials and individual layer trials were used as the basis for design changes made in each successive SAS assembly and modifications made in existing hardware.

General laboratory safety rules were enforced during all suited tests. This is particularly true for the altitude chamber runs. Prior to the hypobaric test a safety protocol was submitted to Langley Research Center and approved. A copy of the original document is included in this report as Appendix B. As can be seen by examining the protocol, the test subject's welfare was the primary concern. Before altitude exposure subjects were denitrogenated by breathing 100% O_2 for at least two hours.

As stated above, the objective of the test program was to uncover effects of the SAS on the physiology and performance capabilities of the

wearer and thereby improve the systems wherever possible. The physiological measurements performed were selected in order to uncover effects of the SAS upon three principal body systems--the cardiovascular, the respiratory, and the thermoregulatory. Performance tests were selected to describe the incremental increase in energy cost of activity and the decrements in mobility and dexterity associated with wearing the SAS. In some cases activities were tried simply to see if it were possible for the subjects to perform them. Since comparisons between suited and shirt-sleeve performance were needed, control experiments were run.

The various measurements and tests performed are outlined under the appropriate categories below. Brief statements about the methods used and the purpose of each measurement are included.

Physiological tests and measurements.--

1. Cardiovascular system:

Measurement	Method	Purpose
heart rate*	cardiotachometer (instantaneous rate) via wireless telemetry	index of energy cost of activity and general status of subject
limb volume change	water displacement pleythsmograph	extent of blood pooling and/or fluid extravasation
blood pressure	indirect, standard clinical auscultation and special piezo-electric detector	ppb effects on level; pulse pressure determination; presyncopic warning
orthostatic tolerance	tilt table, 70°	provocative pooling effects

*electrocardiographic signal available simultaneously with same system

2. Respiratory system:

breathing pressure	gage and continuous recording of differential pressure transducer output	
respiratory rate	differential pressure transducer on breathing loop	general status of subject; source of volume calculations

(respiratory system, continued:)

Measurement	Method	Purpose
oxygen consumption	digital O_2 metering device in PPBS when suited; MRM** used for controls	index of energy cost of activity
respiratory volumes	estimated by calculation only	effects of assembly on respiratory mechanics
gas analysis, closed breathing loop		partial pressures of breathing loop diluents; check on
O_2	breathing loop sample, paramagnetic analyzer	CO_2 scrubber function; proficiency of denitrogenation procedure
N_2	sample; Nitralyzer	
CO_2	sample; infra-red analyzer	

**The MRM is an instrument produced commercially by Webb Associates which measures $\dot{V}O_2$ continuously; see Equipment & Techniques.

3. Thermoregulatory system:

skin temperature (T_s)	disk thermistors	measure of surface component of thermal state
rectal temperature (T_{re})	bead thermistor	measure of core component of thermal state
ambient temperature (T_a)	disk thermistor	environmental condition
water loss	weight change	evaporative, diffusive, and respiratory water loss
hemoconcentration	capillary blood, microhematocrit	concentration of circulating blood due to water loss

Performance tests and measurements. --

activity:		
walking	motorized treadmill	measurement of ability to
bicycling	bicycle ergometer	perform and/or incremental
rowing	rowing machine	increase in energy cost
weight lifting	arm pulley device	associated with SAS

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(performance tests and measurements, continued:)

Measurement	Method	Purpose
mobility	flexometers; goniometers; and electrogoniometers	retention of range of movement in SAS for certain set joint motions
dexterity	standard pegboard test	decrement of manipulatory ability due to SAS gloves

Suit counterpressure measurement. -- One additional measurement which became vital during the second test phase was the measurement of garment applied counterpressure. There are no standard methods for measuring the counterpressure applied to the body by elastic garments. Prior to and early in the project we experimented with a variety of techniques, including pneumatic switches and wafer transducers (pressure sensitive paint); however, we were not satisfied with the consistency or the accuracy of the measurements obtained. Miniature strain gage transducers have been used with some success as reported by Ibrahim (Ref. 35), who obtained spot readings under relatively low counterpressure (less than 10 mm Hg) form persuasive garments. Attempts to obtain wide area measurements by moving the transducer under the garments have been made by the Jobst Institute without success. We adopted the technique of placing a blood pressure cuff bladder (13 cm x 22.5 cm) under the garments and pressurizing it. The pressure existing at the moment of separation of the collapsed bladder was taken as the garment counterpressure in the test area. A special device, the Helex bridge, which detects and quantitates length change (with expansion) in an electrically balanced coil (spring), was positioned around the garment over the bladder to detect the inflation point. This instrument was originally developed by Webb Associates to be used in the measurement of limb girth change. The pressure at the inflation of counterpressure point was read from an aneroid gage or recorded from the output of a differential pressure transducer. Although this method tended to produce measurement errors on the high side, it did prove to be reasonably consistent and covered large enough test areas to be useful.

Equipment and Techniques

The instrumentation, equipment, and techniques used in the test program are described below. The altitude chamber facility used for the hypobaric tests is located in the Department of Preventive Medicine at the Ohio State University. A description of this facility is included in the safety protocol presented as Appendix B of this report. Organization of the outline presentation is based on that used in the preceding section.

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Instrumentation used for physiological measurements. --

1. Cardiovascular system

a. Heart rate (HR): Heart rates were routinely monitored throughout each suited and control test. A wireless telemetry-tachometer system was used (Biolink, Model 368, and Biotach, Model 4710; Biocom, Inc.). The small transmitter package (5.3 cm x 8.6 cm x 1.95 cm; weight, 170 gm) was generally carried by the subject. Low profile electrodes of the Ag-AgCl type were positioned over the manubrium and the left lateral fifth intercostal space. Doughnut shaped pads of thin foam urethane or neoprene were often used in suited tests to prevent gapping around the electrodes. In addition to serving as a signal conditioner for the tachometer unit, the FM receiver supplied an audio pulse and an electrocardiographic output suitable for recording and subsequent wave form analysis. The system is designed for operation at up to 100 yards from the subject, and good signals were obtained even through the steel walls of the altitude chamber.

b. Limb volume change: The subject's bare limb volumes were determined before and after many suited experiments. A water displacement pleythsmography technique was used. Two special Lucite cylinders were fabricated and calibrated for this purpose. The smaller cylinder (9.8 cm ID x 70.5 cm height) was used for arm volume determinations, and the larger cylinder (15.7 cm ID x 70.2 cm height) was used for leg volume measurements. The smallest possible diameter cylinder was selected in each case to reduce the measurement error. A sight tube was made of 1.25 cm OD Lucite tubing and was equipped with a sliding device which was set at the post-immersion meniscus level. The calibration was cc/mm, and readings were taken from a steel millimeter tape which was positioned along the reading tube. Arms were immersed to a level approximately 6 cm below the axilla, and the leg was immersed to the knee only. Marks were made on the body so that pre- and post-test immersion levels could be duplicated. The same temperature was used for each pre- and post-test measurement. The cylinders were leveled prior to each measurement.

c. Blood pressure: Blood pressures were routinely monitored during tilt table tests and occasionally during other test procedures. Two indirect methodologies were used. Standard clinical manual sphygmomanometric techniques were generally used during shirt sleeve control tests. Korotkow sounds were detected with a stethoscope positioned over the brachial artery. Auditory detection of these sounds through the garment layers proved to be unsatisfactory; therefore, a special system was developed which produced an electric analog of the Korotkow sounds which could be recorded. A standard cuff was positioned over the garments in the normal clinical position, inflated manually to more than 200 mm Hg, and allowed to deflate over a 30-45 second period. The cuff was equipped with a ±255 mm Hg differential pressure transducer (Statham Instruments, Inc.; Model PM6TC±5-350), which provided

a signal proportional to cuff pressure as referenced to ambient pressure. The arterial pulse sounds were detected electrically by a small piezoelectric crystal positioned over the brachial artery under the cuff. The response of the crystal was actively filtered at a peak of 35 Hertz with the resultant biphasic wave form superimposed on the cuff pressure curve. Pulse wave forms characteristic of systolic and diastolic end points were discernible.

d. Orthostatic tolerance: Unbalances in pressurization between the SAS and the circulatory system may result in venous pooling or other distributional losses to the circulating blood volume. These effects are normally aggravated in the orthostatic configuration brought on by passively tilting a subject. Therefore, the tilt-table test was selected as the most severe circulatory stress we could impose on our suited subjects. In the procedure selected, the subjects, after spending ten minutes relaxing horizontally on the table, were tilted over a ten second period to an angle 70° from the horizontal. The subjects were retained in the tilted position for periods up to 20 minutes, during which time blood pressure and heart rate were monitored on a minute-to-minute basis. Shirt sleeve controls were run using the same techniques. The table used is padded with a foam plastic mat and a specially constructed "saddle" for the comfort of the subject. No foot rests were used.

2. Respiratory system

a. Breathing pressure and respiratory rate: Both breathing pressure and respiratory rate were always monitored during suited tests. Although the indication of breathing pressure was always available to the subject and observers from aneroid pressure gages, a continuously recorded analog was also obtained. A ±260 mm Hg (5 psid) differential pressure transducer (Statham Instruments, Inc.; Model PM6TC-±5-350) which referenced the breathing loop pressure to ambient was the source of the signal. Respiratory rate was obtained simultaneously by a second transducer of the same type; however, the transducer was referenced to the dome pressure set-point for the PPBS regulator package. Amplification of the signal produced by the slight instantaneous pressure fluctuations in the breathing loop associated with breathing gave us the respiratory rate. The transducers were the strain gage type and excited by 10 VDC.

b. Oxygen consumption ($\dot{V}_{O_2}$): During suited tests, subject $\dot{V}_{O_2}$ could be determined from the output of the digital oxygen metering device (DOMD), which is described in the PPBS section of this report. The injection of individual 100 cc (STPD) increments into the breathing loop triggered a pressure switch in the DOMD. Each switch closure signalled the injection of 100 cc O_2. The output was totalized by an electronic counter or recorded as an event on a strip-chart recorder. Some problems were experienced in the use of this prototype device. For example, system leak rate had to be determined and subtracted from the total injected volume in order to obtain $\dot{V}_{O_2}$. Also,

subject movement which resulted in loop pressure fluctuations of sufficient magnitude would trigger false $\dot{V}_{O_2}$ injections. Subject bending would compress the breathing bladder, causing an increase in loop pressure. If the increase exceeded the helmet relief valve set-point, a volume of gas was dumped overboard. Excess volume dumped, if any, was then made up by the DOMD as the original conditions were restored. Leak rates were determined by counting injections during a breath-hold by the subjects. To prevent false triggering, the breath-hold was started at end expiration. The DOMD was calibrated and found accurate (see PPBS); however, since the device was pressure actuated, care had to be exercised during measurement periods to avoid non-$\dot{V}_{O_2}$ related pressure fluctuations.

For the measurement of shirt sleeve control levels of $\dot{V}_{O2}$, the Metabolic Rate Monitor* (MRM) was used. This instrument measures $\dot{V}_{O2}$ continuously. A servo-controlled blower draws room air through a facepiece, adjusting its volume flow so that oxygen tension downstream from the man is kept essentially constant. The indicated and recorded error signal in the servo loop is continuously proportional to oxygen consumption. This measurement compares favorably with measurements made with Douglas bag collection and gas analysis. The response time of the instrument is several times faster than the apparent response time of oxygen consumption when the man changes his work level.

c. Respiratory volumes: Respiratory tidal volumes and vital capacities of suited subjects could be estimated from the instantaneous pressure variation seen in the closed loop which were associated with breathing. In order to avoid complex calculations which would be required to analyze the simultaneous variables, an empirical calibration procedure was used. During a quiescent period (e.g. breath-hold by subject) the DOMD was made to inject 100 cc increments into the complete loop. Since the volume of the loop was assumed to be fixed, the resulting pressure charge associated with each injection (or a series of injections) allowed us to make correlations between system volume vs. pressure changes such that:

$$V_i = -\Delta P \times C$$

$$V_e = +\Delta P \times C$$

where: V_i = inspired volume; V_e = respired volume; ΔP = the change in breathing loop pressure in mm Hg; and C = constant derived from $\Delta V/\Delta P$ relationship with a mean value of 40 cc/mm Hg for the temperature and pressure conditions which prevailed. The error in this estimation is potentially large; however, direct measurements with a respiratory flowmeter were precluded due to lack of space in the helmet.

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*U. S. Patent No. 3,401,683.

d. Gas analysis: At various times throughout the test program samples of circulating gas were taken from the breathing loop for analysis of O_2, N_2, and CO_2 content. In the laboratory only CO_2 analyses were performed in order to determine the proficiency of the PPBS CO_2 scrubber. Sample balloons were filled by the positive pressure in the loop and immediately analyzed for CO_2 content on an infra-red analyzer (L/B 15A, Beckman Instruments). During altitude chamber tests above 45,000 feet, samples were pumped from the breathing loop for analysis of all three gases. We were primarily interested in determining the percentage of diluent gases (N_2 and CO_2) so that a safe pO_2 was available to prevent hypoxia. Nitrogen content was measured with a Nitralyzer[R] (Med-Science Electronics, Model AR205). Oxygen and CO_2 content were measured on paramagnetic and infra-red analyzers respectively (Beckman Instruments, Inc., Models E and L/B 15B respectively).

3. Thermoregulatory system

a. Skin temperatures (T_s), rectal temperatures (T_{re}), and ambient temperatures (T_a): All these were monitored during several laboratory and altitude chamber tests. Both T_s and T_a were sensed by disk thermistors (YSI #425), and T_{re} was detected by standard thermistors (YSI #401) inserted to a depth of 10cm into the rectum. Temperatures from six different sites on the skin were sampled. The T_a probe was generally housed on the PPBS. All temperatures were recorded from the output of a digital thermometer (United Systems, Inc., Digitec Model 501). The purpose of all temperature measurements was to assist in determining any thermal burden imposed by the SAS system and in particular to determine the initiation of evaporative cooling and its effect on T_s during altitude tests.

b. Water loss: Body water loss in subjects was determined by weight change across an experimental period. No attempt was made to differentiate the quantity of water loss by the various pathways--evaporative due to sweating, diffusive, and respiratory. This measurement was primarily reserved for the altitude tests, since it was here that water loss rate could be a potential problem.

c. Hemoconcentration: When fluid is lost from the circulating blood volume, hemoconcentration results. An increase in packed red blood cell volume (hematocrit) is a measure of this loss. Water loss by sweating and fluid loss by extravasation into body tissue may cause an increase in the hematocrit. Therefore, microhematocrit determinations were made on several occasions using an electronic hematocrit device (YSI, Model 30). Capillary blood taken from the finger of the subject was used.

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Instrumentation Used for Performance Tests and Measurements. --

1. Ergometric activities

Several forms of ergometric tasks and activities were used to determine the incremental increase in energy expenditure associated with wearing the SAS or as tests of performance capabilities. Included in these activities were treadmill walking at speeds from 2.4 to 4.8 km/hr, and bicycling on a bicycle ergometer at the work rate of 1 kpm (kilopond meter/min). These may be categorized as standing and seated leg work respectively. Seated arm and back work was tested on a rowing machine device at the rate of 20 strokes per minute. Standing arm and back work was performed using an arm pulley device. Shirt sleeve controls were performed by the subjects on those tests for which suited $\dot{V}_{O_2}$ measurements were made.

2. Mobility tests

Tests for mobility and range of joint movement were performed on shirt sleeved and suited subjects. Electrogoniometers were constructed following a design developed by Karpovich (Ref. 36). Electrogoniometric measurements were made on the elbow and knee joints during bicycling and rowing activities. A selected number of range of joint motion measurements was also made using Leighton flexometers and protractor goniometers. The flexometer consists of a weighted 360° dial and a weighted pointer mounted in a case. The dial and pointer operate freely and independently; the movement of each is controlled by gravity. Independent locking devices are provided for the pointer and dial disks. This instrument and its use have been described in the literature (Ref. 37).

3. Dexterity tests

Tests to determine the decrement in dexterity associated with wearing the SAS gloves were performed. Barehand and gloved tests were made using the Purdue Pegboard. This device has been used to test manual dexterity in full pressure suits (Ref. 38). The apparatus consists of a 12 in. x 18 in. plywood board in which there are two 12 in. columns of 25 holes, each spaced at 1/2 in. intervals. The columns are 1 in. apart. Sized steel pins, collars, and washers are stored in cups at the top of the board. During a timed test period, the subject inserts pins and/or makes as many assemblies (pin-washer-collar-washer) as he can, using either the right or left hand or both.

Subjects

Three test subjects, all employees of Webb Associates, were used. Subject selection, in addition to personal interest in the project, was based upon previous test subject experience, particularly with pressure suits,

closed circuit breathing systems, and similar gear. Of the subjects selected, all three are trained divers and two had had previous altitude chamber experience. A level of physical fitness above average for the respective age groups was required. General information and a basic anthropometric description of the subjects is given below.

Subj.	Age[*] yrs	Height cm	Height in.	Weight kg	Weight lbs	Surface[**] area-m^2	Occupation & Qualifications
A[***]	37-38	183	72	70	154	1.9	resident physiologist; broad test subject experience; diver; altitude chamber experience
B	45-46	173	68	73	160	1.85	physician & physiologist; broad test subject experience including pressure suits, respirators, etc.; diver
C	30-31	168	66	69	152	1.78	draftsman & designer; test subject experience; trained Navy diver

[*]The project covered a two-year period.

[**]After DuBois and DuBois (Ref. 39)

[***]This subject developed a respiratory problem early in the test phase and was dropped from further testing as a precautionary measure.

Many additional anthropometric measurements were taken of each subject (see Garments), which were necessary for garment engineering; they have not been included in this report since they would be superfluous. It is of interest that subjects B and C were judged to be sufficiently similar in major body dimensions that parts of the final assembly (SAS #10) were shared without sacrificing fit or significant amounts of counterpressure.

RESULTS

The testing program can be broken down into the following four parts:

1st Phase: 1. Laboratory tests (1-1 to 1-15)
2. Altitude Chamber tests (2-1 to 2-5)

2nd Phase: 3. Laboratory tests (3-1 to 3-15)
4. Altitude Chamber tests (4-1 to 4-3)

The suited tests performed in each of these periods are summarized and listed sequentially in Table II. The experiments are numbered according to the sequence given above. As explained earlier in the report (see Methods) each of the laboratory test series was preceded by a development period during which time individual layers were donned to determine fit, solve design problems, and work out system integration schemes. Very often data were not obtained in conjunction with these trials, and they are not included as part of Table II. Also, control or shirt sleeve tests are not included. The subject, the suit configuration, and the time spent during each test in positive pressure (above ambient) breathing are listed in the table. The positive pressure breathing period, called "helmet time," was chosen as the best index of the test time, since the helmet was routinely donned immediately after the first layer was in place and doffed as the same garment was removed. The breathing pressure varied throughout the course of a given experiment; however, the target pressure in a partial assembly or full assembly test was always selected to balance the counterpressure thought to be supplied by the garments.

Donning time, or dressing time, varied depending upon the assembly and the amount of bioinstrumentation used. Generally for a complete assembly the donning time averaged from 45 to 60 minutes. We were not successful in developing techniques for simultaneous multiple layer donning, which would have significantly reduced the required dressing period. Doffing, or undressing, time for a complete (170+ mm Hg) assembly averaged 7 minutes during the first phase and five minutes during the second phase.

In the various full assemblies, wear times ranged from a minimum of 18 minutes (based upon helmet time) to a maximum of 160 minutes. Shorter experiments usually resulted from some equipment failure. Longer experiments were terminated after attainment of test goals or due to subject fatigue. No conscious attempt was made to establish a maximum wear period for either partial or full SAS assemblies. There is little evidence from our studies that assemblies requiring up to 100 mm Hg breathing pressure for balance could not be tolerated indefinitely. Assemblies that theoretically require breathing pressures in excess of 130 mm Hg appear to be time

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limited to approximately 3 hours wear by the moderately active subject. The limiting factor in the higher pressure experiments, in addition to generalized physical fatigue, usually manifested itself as an elevation in heart rate. This phenomenon will be discussed in the following sections, where findings from the physiological tests performed in both laboratory phases are given, arranged generally in accordance with the system used in the Methods section. A final section follows which covers the results obtained in the altitude chamber tests.

Table II. Log of Suited Laboratory and Altitude Chamber Tests

Test No.	Subject	Assembly configurations	Helmet time (mins)
Laboratory-- 1st phase			
1-1	C	SAS#4, full (170 mm Hg equivalent)	55
1-2	C	" partial (100 " " ")	69
1-3	B	SAS #5, full	100
1-4	C	SAS#4, partial	53
1-5	C	SAS #6, full	62
1-6	C	SAS #6, full	160
1-7	B	SAS #7, full	111
1-8	C	SAS #6, full	56
1-9	B	SAS#5-SAS#7, full with reduced cp on torso	115
1-10	C	SAS#4-SAS#6, full; reduced torso cp	110
1-11	C	SAS #6, partial	90
1-12	C	SAS #8, full	85
1-13	C	SAS #8, full; carried PPBS	123
1-14	B	SAS #9, full; reduced torso & limb cp; carried PPBS	80
1-15	C	SAS #8, full; reduced torso & limb cp; carried PPBS	96
Altitude Chamber-- 1st phase			
2-1	B	SAS #9, full; carried PPBS	86
2-2	C	SAS #8, partial; carried PPBS	70
2-3	C	SAS #8, full; carried PPBS	110
2-4	C	SAS#6-SAS#8, full; carried PPBS	126
2-5	C	SAS #8, full; carried PPBS	69

(Table II, continued)

Test No.	Subject	Assembly configurations	Helmet time (mins)
Laboratory-- 2nd phase			
3-1	C	SAS#6-SAS#8, partial; new neck seal	18
3-2	C	SAS #8, single layer, minimum pieces	47
3-3	C	SAS #8, partial	63
3-4	C	SAS#6-SAS#8, full	89
3-5	B	SAS #7-SAS#9, full	86
3-6	B	SAS#7-SAS#9, full	70
3-7	C	SAS#6-SAS#8, partial, with leg bladders	114
3-8	B	SAS#7-SAS#9, full, with "G" suit	54
3-9	C	SAS#10, partial, with "G" suit	88
3-10	B	SAS#10, partial	60
3-11	B	SAS #10, full, with girdles	87
3-12	C	SAS #10, full, with girdles	100
3-13	B	SAS #10, full, with girdles	94
3-14	B	SAS #10, full, minus girdles	130
3-15	C	SAS #10, full, minus girdles	112
Altitude Chamber-- 2nd phase			
4-1	B	SAS #10, partial	21
4-2	C	SAS #10, full, with girdles	145
4-3	C	SAS #10, full, with girdles	125

Physiological Results of the Laboratory Tests

Cardiovascular.-- As has been stated, positive pressure breathing without proper counterpressure on the torso and limbs leads quickly to pooling of blood in the capacitance vessels. If the resulting reduction in circulating blood volume should reach 200 to 800 cc, one would expect to see pronounced tachycardia followed by bradycardia and then syncope in a matter of minutes. Except for some elevation in heart rates, we did not see such signs after more than two hours of wearing the SAS in the laboratory tests. In ground level tests with breathing pressures of more than 170 mm Hg, not a single case of syncope was experienced. Pooling, therefore--one of the major physiological problems in partial pressure suits--has been avoided by the way we applied counterpressure to the limbs with the SAS.

Tests of circulatory sufficiency verified the adequacy of venous return during high positive pressure breathing. First, it seemed remotely possible

that despite the clinical evidence of limited pooling, the limbs might never-theless have accumulated edema fluid if venous pressure was high. Pooled blood quickly returns to the circulation once tolerable pressure balances are re-established, and actual measurable changes in limb volume may not occur. The extravasated fluid of edema returns more slowly, and this can be detected as a change in limb volume. To test for this, we measured volumes of the arm and lower leg by a water displacement technique before and after many experiments. In 17 measurements on two subjects (B and C), lower leg vol-ume never increased more than 10 cc. Since this amount was comparable to the measurement accuracy, it is doubtful if any change occurred. Arm vol-ume change varied; in 20 individual measurements, the average increase was 35 cc. The average rate of increase was 25.9 cc/hr, regardless of breathing pressure. Most of the swelling was restricted to the hands, and the amount detected was more directly related to the misplacement or late placement of the rounding pads under the gloves than to the breathing pressure. Although low volume changes (about 7.5 cc) were noted on occasion, we were never able to completely eliminate hand swelling. In the attempt to obtain correct amounts of volume change, measurements were always made immediately before dressing and immediately after removal of the last garment layer. Since the helmet was removed, hence the positive pressure breathing dis-continued, prior to the measurement, garment squeeze may have acted to reduce the volumes obtained. Attempts to obtain on-line indications of volume change in limbs using the Helex bridge device (see page 60) were unsuccessful due to the extreme sensitivity of the instrument to muscle tremor or move-ment.

Another test of circulatory sufficiency performed was the standard test for orthostatic tolerance on a tilt table. Both subjects (B and C) per-formed this test in the control (shirt sleeve) and suited configuration. After a 10-minute period of resting horizontally, the subjects were passively tilted over 10 seconds to an angle 70° from the horizontal for 15 to 20 minutes. Heart rate and blood pressure were monitored during each test. Control and suited data are compared graphically in Figures 38 and 39 for subjects B and C respectively. During the suited test, subjects breathed O_2 at 135 to 140 mm Hg.

Control blood pressures were determined using standard clinical sphygmomanometry techniques. Korotkow sounds and pressures were de-tected in the suited tests by an electronic transducer system (see page 61). The blood pressures in both control runs showed an initial narrowing of pulse pressure which was due primarily to the elevation in diastolic pressure. The pulse pressure band width was maintained throughout the remainder of the tilt period. Both subjects in the suited condition showed an unexplained shift in both systolic and diastolic pressures upon tilt; however, the new pressure levels were maintained throughout the tilt. Neither subject showed
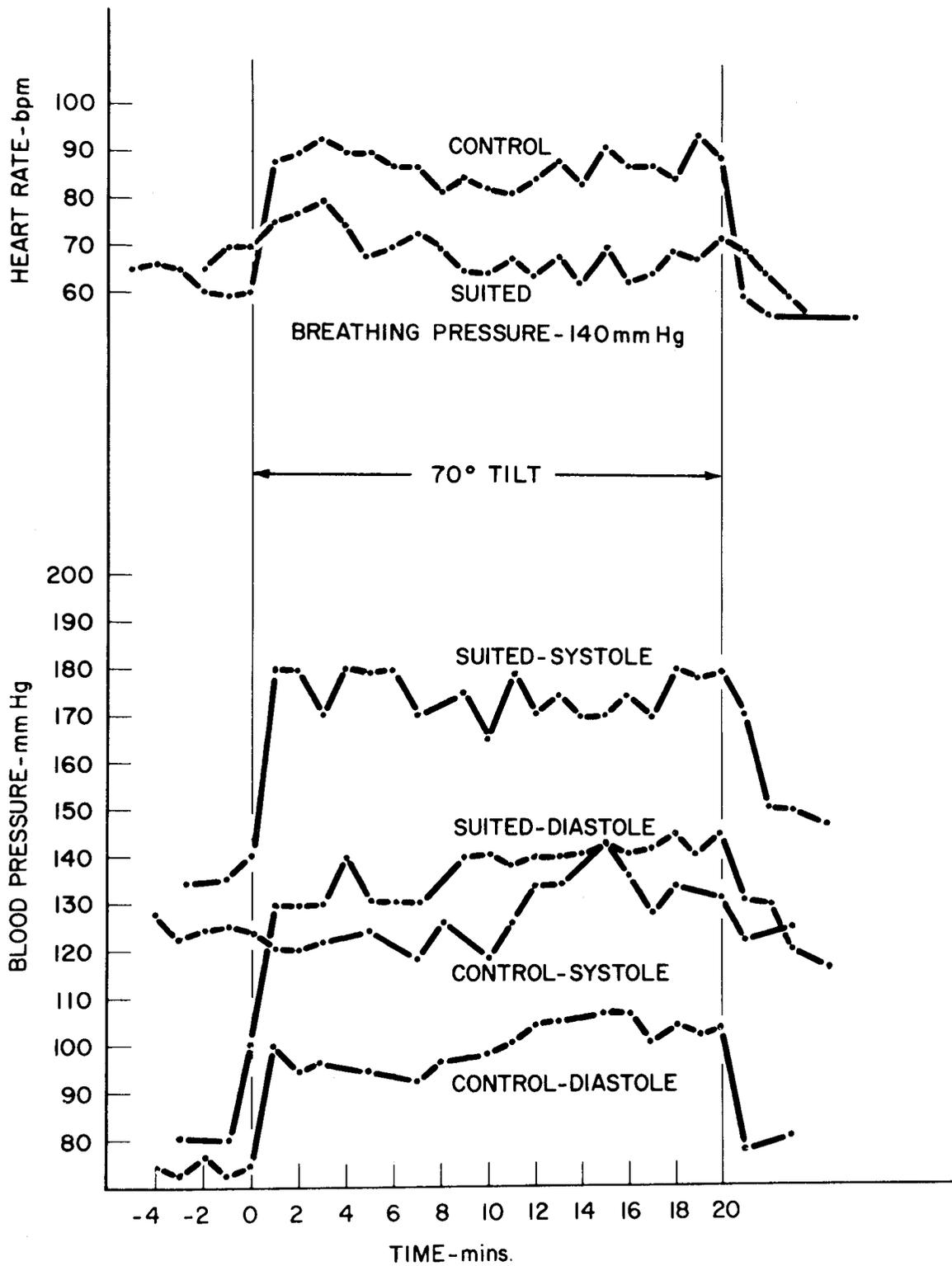
Figure 38. Suited and shirt sleeve control heart rate and blood pressure response to 70° tilt, Subject B.
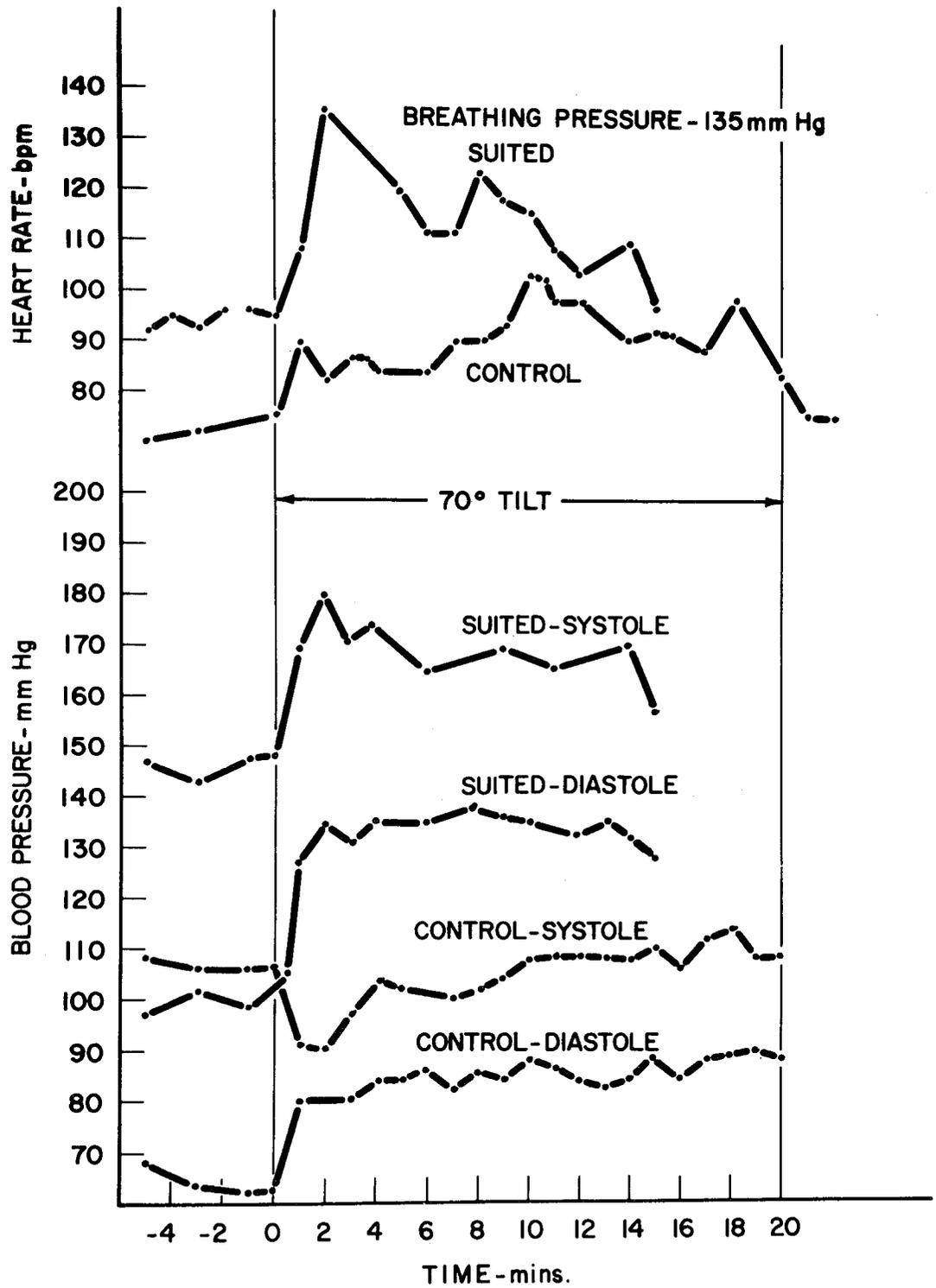
Figure 39. Suited and shirt sleeve control heart rate and
blood pressure response to 70° tilt, Subject C.

signs of impending syncope. The suited tilt for subject C (Fig. 39) was ended after 15 minutes by subject request. In the figures, the general elevation in blood pressure in the suited subjects must be accredited to the difference between the counterpressure supplied by the garments and the increase produced by breathing O_2 at 135-140 mm Hg. Since the measurements were made over the garment layers, and blood pressure is increased by an amount approximately equal to the breathing pressure, the garment supplied counterpressure in the anticubital area in these cases was approximately 120 mm Hg and 100 mm Hg for subjects B and C respectively.

In tests to determine the effects of PPB on blood pressure, a subject (C), wearing a fixed SAS assembly to eliminate variations in suit counterpressure, varied his breathing pressure while blood pressures were determined at each new breathing level. Breathing pressures up to 85 mm Hg were tried. Over the range tried, the blood pressure increased with the breathing pressure in a linear fashion; however, the systolic pressure consistently averaged 10 mm Hg less than that obtained by adding the control value to the breathing pressure. Ernsting (Ref. 3) pointed out that the elastance of the lung reduces the transfer of pressure to the blood stream by a similar amount.

Although Subject C (Figure 39) did show an initial increase in heart rate after tilt, by the end of the test the rate was near control levels. Subj. B, on the other hand, maintained a heart rate lower than control values throughout the tilt period. Neither subject was syncopic at the end of the test. The experiment involving Subject B was performed later in the project, at which time the general suited condition had been improved.

Heart rate levels were raised at higher breathing pressures. During the first phase tests, mild tachycardia appeared at breathing pressures higher than 110 mm Hg and became more pronounced as the breathing pressure increased. At 170 mm Hg breathing pressure, the increase amounted to approximately 25 beats per minute over that usually seen for each subject. This effect was thought to be due to uneven pressurization around the neck area. The neck seal terminated a little short of the base of the neck, and the elastic garments did not apply pressure properly below this point. In the relatively unpressurized region between the top of the torso pressurizing breathing bladder and the neck seal, it seems likely that barorecepters in the carotid sinus may have been stimulated. During the second phase, the neck seal-garment interface area was redesigned so that pressurization was improved (see Figures 34 and 37), and the incremental increase in heart rate was lowered by this change. Early in the project it had been noted that heart rates showed a transient and an immediate decrease following a reduction in breathing pressure. This response was thought to be due to the influx of venous blood into the pulmonary circuit as the pressure was dropped, and

would be expected whether the volume of venous blood had been trapped because of insufficient garment counterpressure or not. Still, we decided to investigate the problem. An area of low garment counterpressure was discovered in the upper thigh region by in situ measurements. Using an Air Force "G" suit over the garments, pressurized to or slightly above the breathing pressure, the heart rate response was lessened. We, therefore, decided that some pooling had been occurring in the upper leg-lower abdomen interface area, and the two powernet "overgirdles" were added to the SAS #10 assembly.

Respiration.-- Early in the project subjects had real difficulty in breathing. This was thought to be due to the effect of as many as four layers of heavy powernet fabric over the torso breathing bladder. Shallow breathing with tidal volumes estimated to be 250-300 cc per breathing required little effort. Work requiring increases in respiratory tidal volumes in excess of 1 liter per breath could not be maintained for more than a few minutes. Tidal volume appeared to be limited near the high end of the vital capacity. Increasing the breathing loop pressure in an attempt to equalize bladder pressure and suit counterpressure did not seem to improve the situation. Different bladder or loop configurations were tried, including placing the bladder "in line" and "T'd" off the loop without significant improvement. Later in the first phase tests, the amount of elastic counterpressure furnished to the torso was reduced. This allowed the bladder to do the job of volume compensation--that is, to expand with exhalation and contract with inhalation. When the breathing bladder supplied most of the torso counterpressure, the breathing was subjectively effortless and respiratory rates were only slightly higher than those usually observed in these men. As a result of these findings, the use of the heavy powernet fabric on the torso was abandoned. Without matching garment counterpressure, the bladder tended to balloon, making torso bending difficult. Therefore during the second phase bladder restraint garments of non-stretch Nomex fabric (see pp. 29-31) were used to limit expansion and fix the maximum bladder volume to approximately 6 liters. The vital capacities of the principal subjects were 4.18 and 3.7 liters for subjects B and C respectively. The interconnection of the helmet and the bladder developed during the second phase tests (see Figs. 14, 36, and 38) further reduced the work of breathing. Throughout the project at breathing pressures in excess of 100 mm Hg, subjects felt that compression of the abdominal wall caused an up shift in the diaphragm, causing the breathing to be out of the top end of the vital capacity. Increases in the breathing pressure did not seem to correct this problem.

Respiratory rates were often observed as part of the test routine. Data from more than 20 experiments in which respiratory rates were monitored showed average resting rates of 13 and 17 breaths per minute for subjects B and C respectively. No consistent relationship between breathing rate and breathing pressure was observed; however, one subject (B) often showed

a slight decrease in rate (with an increase in tidal volumes) at breathing pressures above 130 mm Hg in the final bladder configuration. This same subject has a natural tendency toward Cheyne-Stokes breathing patterns in which a period of apnea is followed by a period of compensatory hypernea. During moderate work on the bicycle or treadmill, subject respiratory rates averaged 30 breaths per minute, a rate not considered excessive at the level of work (5 - 7 kcal/min).

Samples of gas were taken from the breathing loop on several occasions for analysis of content. This was particularly true during the altitude chamber runs where the level of diluent gases was critical. In the laboratory the accumulation of CO_2 due to PPBS scrubber inefficiency was of interest. Determinations made consistently showed CO_2 levels of 0.1% to 0.2% after up to 90 minutes of closed loop breathing. A maximum recorded level of 0.85% CO_2 occurred during an altitude run (4-3) after nearly two hours of PPBS use. During altitude runs measurements were made of all three loop gases--O_2, N_2, and CO_2. Since the CO_2 levels were always less than 1%, the principal diluent of concern was N_2. An effort was made to maintain a loop pO_2 of 150 mm Hg (absolute) at all pressures in order to prevent hypoxia. Subjects breathed 100% O_2 for at least 2 hours preceding each altitude test. This amount of denitrogenation is considered to be sufficient to remove 95% of the body's N_2 stores. Despite this estimate, measurements disclosed loop N_2 contents as high as 17% during one early altitude run. During the second phase altitude tests, more care was used in flushing the bladder and helmet during donning.

Thermoregulation. -- Dissipation of metabolic heat through the open mesh of the elastic material was adequate during moderate exercise (5-7 kcal/min) in the laboratory. Heavy work (10-15 kcal/min) was not performed in the assembly. No effort was made to determine the temperature limits of the SAS suited subjects, and all laboratory experiments were performed at ambient temperatures ranging from 20 to 30°C at approximately 50% relative humidity. During longer experiments with more activity, some subject sweating was reported; however, evaporation through the fabric on the limbs afforded some cooling. Occasionally a floor fan was turned on the subject to assist the evaporative process. Sweat could not evaporate under the impermeable breathing bladder.

Skin, rectal, and ambient temperature records from two laboratory experiments are plotted graphically in Figures 40 and 41. In both experiments the skin temperatures in the five sites sampled increased slightly; however, the ambient room temperatures increased by a similar amount. Late in each experiment, while the subjects performed activities such as bicycle ergometer and rowing machine work, the floor fan was turned on to assist in cooling. As can be seen in the figures, the limb temperatures decreased, showing evaporative cooling, while the torso temperatures under
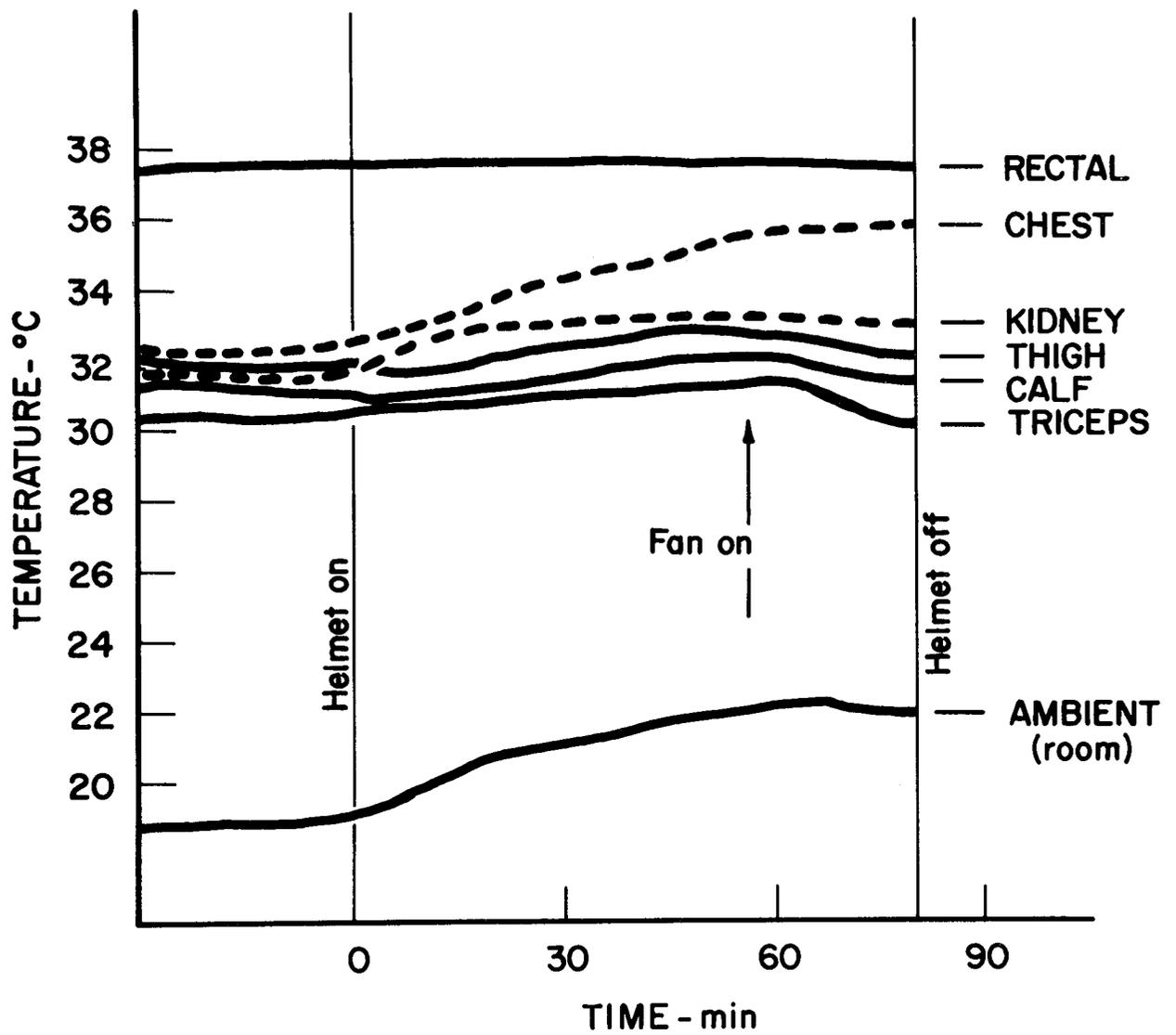
Figure 40. Rectal, skin, and ambient temperatures during
laboratory test 1-14, Subject B.
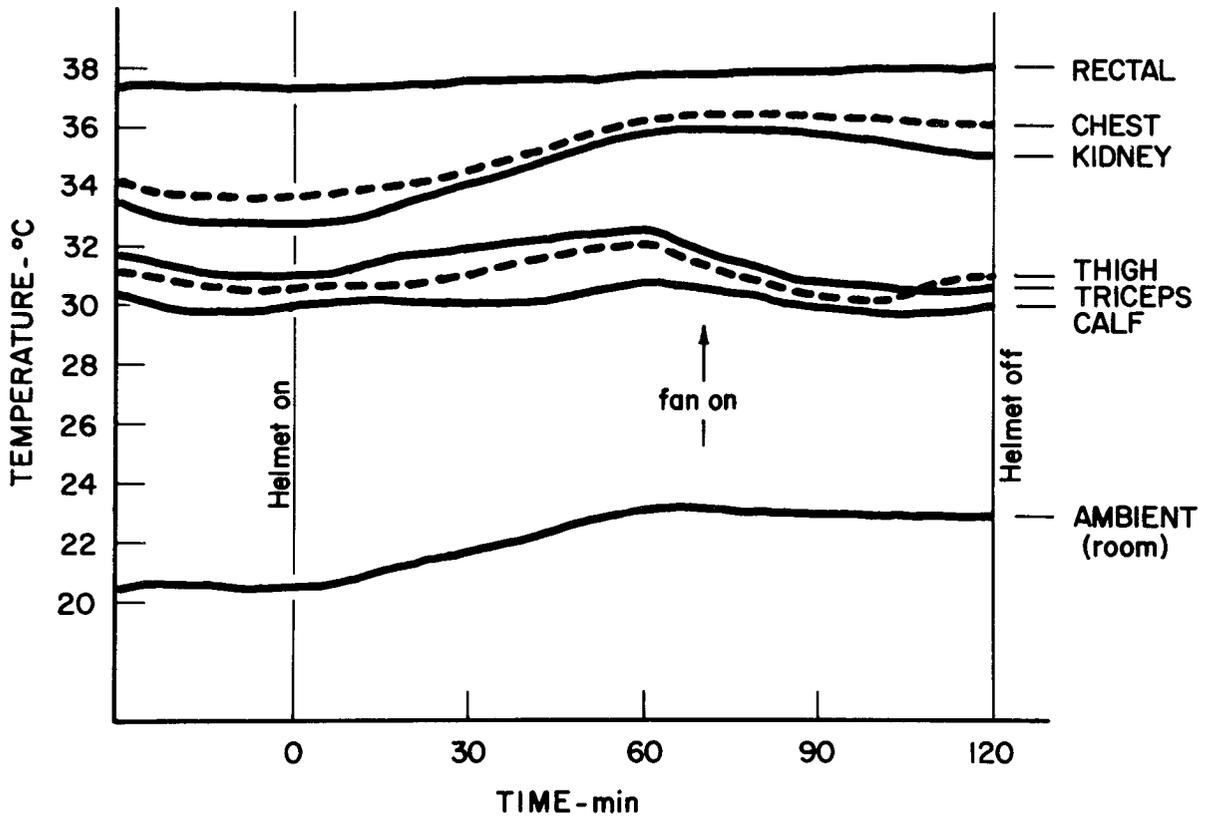
Figure 41. Rectal, skin, and ambient temperatures during
laboratory test 1-12, Subject C.

the bladder remained elevated. Almost all of the net increase in mean skin temperature ($\overline{T}_s$) during the experiment may be accredited to the change seen under the bladder. Although there was some increase in core temperature (rectal--T_{re}), it is doubtful if the change signalled a significant increase in body heat storage, since both experiments were run during the early afternoon hours during a period of normal upswing in the diurnal cycle for these subjects. Six layers of elastic fabric (the maximum number used) were worn by the subjects. Therefore, it is likely that even in the worst case the SAS represented no thermal burden under average ambient conditions for periods of two hours or more. Evaporative water loss based on nude weight change during these two experiments averaged only 83 gm/hr for subject B and 80 gm/hr for subject C (Figs. 40 and 41 respectively). Since insensible water loss (including respiratory) may average nearly 30gm/hr under similar environmental conditions, it is unlikely that frank sweating occurred. Skin and rectal temperatures were monitored during several additional laboratory experiments at similar environmental temperatures; the results were very similar to those presented in Figures 40 and 41.

Additional information relative to thermoregulation will be given in the Altitude Chamber Tests section, which is presented later in the report.

Performance Testing in the Laboratory

Energy cost of activity. -- One of the most inclusive measures of suit performance is the energy cost of activity. The most direct measurement of energy expenditure is oxygen consumption or uptake ($\dot{V}_{O_2}$). For each liter of oxygen consumed, approximately 5kcal of heat energy is produced. SAS suited subjects engaged in various forms of ergometric procedures and other exercise activities in order to determine the incremental increase in energy cost associated with wearing the garment. Three forms of activity for which both control and suited data were obtained are listed in Table III.

Walking suited on the treadmill at speeds of 3.2, 4.0, and 4.8 km/hr resulted in an average energy cost increase of nearly 1.4 times over the control values. Measurements were taken from the 4th to the 5th minute of work at each level. Suited $\dot{V}_{O_2}$ was obtained from the output of the DOMD in the PPBS (see PPBS section). The SAS #10 assembly (without girdles) was worn by both subjects, and the breathing pressures during the treadmill test were 140 mm Hg and 110 mm Hg for subjects B and C respectively. The PPBS was not carried by the subjects. Heart rates during the suited runs showed a slight increase over those predicted from the increased $\dot{V}_{O2}$, averaging 1.6 times the control values. Most of this discrepancy may be accredited to the disproportionate increase in heart rate versus $\dot{V}_{O2}$ seen in subject C, who reached heart rates of 150 and 170 beats per minute near the end of the two work periods reported. The increase in energy cost of walking in pressurized full pressure suits is usually much higher than that found with the SAS.

Table III. Energy Cost Values for Working in the SAS

Activity	Subj.	Work Rate	Energy Cost Control kcal/hr	Energy Cost Suited kcal/hr	No. of times energy cost is increased with suit[*]
treadmill walking	B	3.2 km/hr	240	360	1.50
		4.8 km/hr	330	450	1.36
	C	3.2 km/hr	180	210	1.17
		4.0 km/hr	180	270	1.50
bicycle pedalling (ergometer)	B	300 kgm/min	255	480	1.88
		450 kgm/min	345	570	1.65
	C	300 kgm/min	375	630	1.68
rowing	B	15 strokes/min	325	720	2.2
	C	15 strokes/min	405	750	1.85

[*] average increase: 1.64 compared to 2.26 for Apollo and Gemini suits. See Table I, page 6.

As noted, the average increase seen while walking in pressurized Gemini and Apollo suits at speeds from .6 to 3.2 km/hr is 2.4 times estimated nude values for the data presented in Table I (see Introduction). We have not found any reports of walking at speeds in excess of 4.0 km/hr (2.5 mph) in a pressurized full pressure suit in the 1G environment. In our tests, one of the subjects (B), while walking at 4.8 km/hr, actually showed a lower increase in energy cost than experienced at the slower speed; his increased efficiency at the higher speed probably resulted from an observable tendency to walk with better general coordination of limb acceleration and deceleration.

Also included in Table III are the energy cost data obtained from bicycling and rowing. The increase in energy cost ascribable to the SAS in these activities is slightly higher than that produced by walking on the treadmill. This effect may be partly explained by the fact that these experiments were run earlier in the project than the treadmill exercise, hence earlier garment assemblies, which were more restraining, were worn. In addition,

despite the fact that in both instances the subject was seated, the PPBS was carried, and some amount of energy was required to stabilize the weight and to accelerate and decelerate it. No comparative bicycling data for a full pressure suit could be found in the literature; however, Streimer, et al (Ref. 40) reported an increase in oxygen cost associated with arm work in three unidentified full pressure suits of 2.1 times control levels. This activity may be similar to our rowing task, which showed a similar increase. Since the rowing device used is not an ergometer such as the treadmill and bicycle, the amount of work performed cannot be stated in work terms and direct comparisons are difficult.

Other forms of activity were also attempted in the laboratory by suited subjects. These activities included arm pulley work; stepping up and down a 38 cm (15 in.) step; and climbing on a ladder treadmill. The subjects were able to perform the arm work quite satisfactorily; however, $\dot{V}_{O_2}$ levels were not obtained and work periods were short, lasting less than 2 minutes. Stepping and climbing on the ladder treadmill were abandoned as procedures after early trials, being judged as unsafe for the suited subject. In both instances complete visibility of the feet at all times is mandatory to avoid tripping or entanglement. Although subjects in the SAS could flex the torso sufficiently to see their feet over the helmet rim, maintenance of the required position made the subjects unstable. No attempt was made to test endurance times for the various forms of activities. We were mainly interested in establishing the energy cost of the SAS.

Mobility and dexterity. -- The SAS suited subjects possessed a reasonable amount of mobility, as evidenced by their ability to perform the activities mentioned above. In 100 mm Hg equivalent assemblies, subject mobility was extremely good; however, actual measurements of ranges of motion were not made in this configuration. Earlier in this report it was mentioned that one of the goals for the SAS was to demonstrate improved mobility over the full pressure suits. We were only partially successful in attaining this goal. A review of the literature on mobility measurements in full pressure suits revealed one consistent fact--complex motions involving 3 degree of freedom joints are restricted. The tilting and rotation of the pelvis required for balanced locomotion is limited, making walking difficult. Walking in the SAS was quite acceptable, and subjects did not complain of a feeling of unbalance, particularly when the PPBS was carried.

In an effort to determine where the mobility in the SAS was restricted, a series of measurements of range of joint movement was performed. The results of these measurements are summarized in Table IV. The range of movement is expressed as the angular excursion in degrees for the motions listed. Measurements were performed using Leighton flexometers (see Equipment and Techniques), except for movement #5 (Table), which was

Table IV. Range of Joint Movement in the SAS

Movement[*]	Subject B nude suited range in degrees		Subject C nude suited range in degrees		% retention-- suited vs control Subj. B Subj. C	
	nude	suited	nude	suited	Subj. B	Subj. C
Wrist; flexion & extension, frontal plane	104	99	115	112	95	97
Forearm, supination & pronation, frontal plane	174	130	172	122	75	71
Elbow, flexion & extension	135	130	148	124	96	84
Shoulder, adduction & abduction in frontal plane	120	74	122	74	62	61
Shoulder, flexion & extension in sagittal plane	225	135	210	125	60	60
Shoulder, rotation in sagittal plane	145	142	148	157	98	106
Trunk-hip, flexion & extension in sagittal plane	62	56	67	35	90	52
Trunk-hip, lateral flexion in frontal plane	59	23	58	25	39	43
Hip, abduction & adduction in frontal plane	33	22	36	13	67	36
Hip, flexion & extension in sagittal plane	93	38	96	52	41	54
Knee, flexion & extension in sagittal plane	137	87	145	75	64	52
Foot, flexion in sagittal plane	---	---	67	55	--	82

[*]See Jones (ref. 41) for comparable data in three pressure garment assemblies. Also see paragraph 1, page 82.

measured with a protractor goniometer. Movements measured follow a methodology and notation system which has been proposed   (Ref. 41). Twelve of the original 17 movements were performed. The remaining five movements were omitted from our series because of expected inaccuracies, since a restraint table was not used. Care was exercised to restrain our subjects, however, to prevent errors from dualized movements. For the twelve measurements, the combined average retention (nude vs. suited) for our subjects was 71%. Movements involving the arm and shoulder joint showed more than 80% retention in the suited condition. Trunk-hip and hip range of movement in the SAS was less; however, Jones (Ref. 42), who rated mobility for three pressure garment assemblies using similar techniques, does not include data for some of these movements in the pressurized condition. No explanation of the missing data points is given; therefore it must be assumed that subjects were unable to produce detectable amounts of movement when pressurized. In the two comparable measurements of hip flexion-extension and abduction-adduction performed in both studies, the SAS subjects showed an average retention of 51% and 48% versus an average of 15% and 47% for the respective movements in the three pressure garment assemblies. The reduction of mobility in the hip area with the SAS, although still less than that with pressure garment assemblies, may be accredited to the stiffening effect of the torso pressurizing breathing bladder combined with the additional force applied to the crotch area by helmet pull on the garments.

Electrogoniometric measurements were made of elbow and knee joint movement while pedalling the bicycle ergometer and while stroking the rowing machine. Inspection of the strip chart recordings obtained during the procedure quickly showed almost exact duplication of both angular excursion and wave shape in the suited and nude tests. For this reason an analysis of the data is not presented in the report. It is felt that the nature of the selected exercise routines forced the subjects to perform in nearly an identical manner. For example, the arms (i. e. elbows) were relatively motionless on the bicycle, whereas the legs (i. e. knees) were forced to describe the same circular path by the pedal.

The ability of the subjects to perform various manual tasks while wearing the SAS gloves was observed many times during the laboratory tests. In addition to the handling of various components related to the SAS system, twisting knobs on instruments, and the like, subjects were able to pick up coins from smooth surfaces. Unfortunately, such operations produce no hard data. Therefore a standardized test of dexterity--the Purdue Pegboard test-- was selected as the measurement procedure. The Purdue Pegboard had been used in previous studies with full pressure suits (Pierce, Ref. 38, and Jones, Ref. 42). The results of the pegboard study with SAS gloved subjects are summarized in Table V. The average number of pins placed or assembly components positioned by two subjects in three trials each for barehanded and gloved tests is listed in the Table.

Table V. Purdue Pegboard Scores

Configuration	Right (R)	Left (L)	Both (B)	Assembly (A)
	number of pins placed in 30 secs.			no. of components/60 secs.
Barehand control*	17	16	26	45
SAS glove--no pads*	14	13	20	31
% of control	82	81	77	69
SAS glove--pads**	13	13	18	30
% of control	76	81	69	67

*Score equals average of six trials, two subjects.
**Score equals average of three trials, one subject.

Performance with the SAS gloves averaged 77.7% of the barehanded scores for the single pin placement tests. Performance was slightly lower when the rounding pads were inserted under the gloves and during the assembly task (68% of barehand). Since pin placement data obtained by Pierce (Ref. 38) with the Navy Mark IV full pressure suit shows an average gloved score equal to only 32% of barehand performance when the suit was pressurized, the SAS shows up considerably better. Jones (Ref. 42), in rating three pressure garment assemblies, obtained pegboard single pin scores which averaged 39% of the barehand control. Pressurized vs. barehand assembly scores averaged 20.4% and 27% in the two respective studies. Very similar results have been reported for the A/P-225-2 full pressure suit (Walk, Ref. 43). The higher scores obtained with SAS gloves do not need to be treated statistically in order to demonstrate a significant improvement in dexterity compared with the full pressure suit gloves. The scores presented were obtained while wearing a single pair of SAS gloves which provide a maximum of approximately 100 mm Hg over the fingers. Two pairs of gloves were sometimes worn by subjects during full suit runs. Dexterity, therefore, would be less in the two layers of gloves. The improved tactile sense which is quite adequate even with the dual layer of elastic fabric probably explains the better pegboard scores obtained with the SAS.

Altitude Chamber Tests

The main objective of the laboratory tests was to verify the physio-logical and mechanical soundness of the SAS system in preparation for hypo-baric exposures of subjects in an altitude chamber. The goal for the altitude chamber tests was for a SAS protected subject to attain safely a pressure equivalent to 20 mm Hg absolute (80,000 ft) and remain there for up to two hours. As will be seen in the results to be presented, we did expose subjects to this pressure, but not for the planned two hours. All altitude chamber tests were performed in the facility located in the Department of Preventive Medi-cine at the Ohio State University (see Appendix B). Hypobaric tests were per-formed at the end of both the first and second phase laboratory test periods. A total of eight tests --five in the first phase and three in the second, num-bered 2-1 to 2-5 and 4-1 to 4-3 respectively in Table II--was made by two subjects. Prior to the second phase, revisions were made in the garment assembly, a new helmet was constructed, and certain safety features were added to the PPBS. Details of the modifications or changes in each of these components of the SAS system are given in their respective sections of this report. The objective of the second phase changes was to permit subjects to breathe at pressures up to 200 mm Hg and thereby to increase the margin of safety in the O_2 level at altitude.

Of the five tests completed in the first phase, the first was made by subject B to 10,000 ft (523 mm Hg) to check equipment and to practice emer-gency rescue procedures. The second and third were training tests for sub-ject C (and the observers) to 40,000 ft (141 mm Hg) and 60,000 ft (54.4 mm Hg) respectively. The period of time spent at reduced pressures in these trial runs can be seen in the comparative chamber pressure profiles for all three runs given in Figure 42.

Although these early runs were not necessarily intended for data points, subjects were fully instrumented and monitoring systems were in op-eration. Some of the findings from the three tests were the following:

a. Skin temperatures showed no significant change during any of the experiments.

b. Rectal temperature increased by 0.6°C during test 2 -3.

c. Subject weight loss rate in the three experiments was 60 gm/hr, 95 gm/hr, and 127 gm/hr respectively.

d. No hematocrit change was measured in test 2-1; a change of 1 vol% in hematocrit was measured in test 2-3.

e. Breathing loop CO_2 content did not exceed 0.5% in any of the three experiments.

84
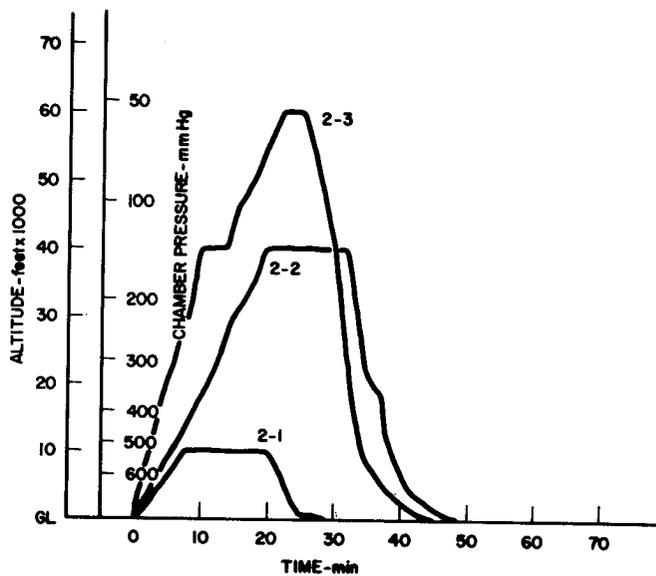
Figure 42. Altitude-pressure profiles for altitude chamber experiments 2-1, 2-2, and 2-3.

f. The breathing loop N_2 content was reduced from initial levels of 5-6% to less than 1% by flush-dumping in tests 2-1 and 2-3; however, in test 2-2 the N_2 level showed an increase with pressure which peaked at 25%. The N_2 was later thought to have been trapped in the bladder and/or helmet during the donning procedure.

g. Subject C reported an "unloading effect" in both the garments and breathing as he passed through the 10,000 ft (523 mm Hg) mark in tests 2-2 and 2-3.

h. Subject activity in the chamber consisted of pedalling the bicycle ergometer (300 kgm/min). In test 2-2 the $\dot{V}O_2$ reached 1.45 lpm (uncorrected for leak) after two minutes of work. Space in the chamber for this type of activity was found to be more limited than expected, and many planned activities had to be abandoned.

i. Heart rates for subjects continued to be elevated, reaching 170 bpm when higher breathing pressures

were tried (150-170 mm Hg). Some of this increase was attributed to subject apprehension and excitement.

j. Respiration rates were comparable to those observed on the ground.

k. No change was detected in leg volume; however, the average arm volume increase in two tests (2-1 and 2-3) was 34 cc.

There were no physiological problems observed during the trial tests which would suggest not to continue testing; therefore two tests with subject C were performed in which the chamber pressure was 20 mm Hg or less. The flight pressure (altitude) profiles for these tests (2-4 and 2-5) are presented in Figures 43 and 44 respectively. As usual, before each test the subject breathed 100% O_2 from a mask for two hours to denitrogenate. The subject remained on O_2 an additional 45 minutes during the dressing and preparation period. Because of the lack of space and difficulty in positioning monitoring cables and the like, no activity such as bicycle pedalling was attempted during these tests for safety reasons.

Test 2-4 lasted a total of 51 minutes from ground level to ground level (GL); approximately 1.5 minutes were spent at a chamber pressure of 20.9 mm Hg (80,000 ft). The chamber pressure was increased at the end of this period to hold at 128 mm Hg (42,000 ft) and then returned to 46 mm Hg (63,000 ft) for several minutes prior to descending to ground level. The decision to terminate the test was based upon general subject fatigue, increased heart rate, and the dangerously high breathing loop level of N_2 (14%). Also, the subject had complained of abdominal pain during the test. After the test it was determined that this condition resulted from gas trapped in the gastrointestinal tract, and the subject was placed on a low residue diet before the next test. Limb volume change was nominal, and weight loss rate (water loss) averaged 97 gm/hr. Hematocrit showed only a 0.5 vol% increase (45.5 to 46 vol%) across the experimental period. Examination of the subject after the test revealed no physical signs of damage resulting from exposure to reduced pressure.

Three days later a second low pressure test (2-5) was conducted (Fig. 44). The entire test lasted 25 minutes (GL to GL). Approximately 1 minute after a chamber pressure of 15 mm Hg (87,000 ft) was attained, the subject, without warning, collapsed. The chamber was immediately recompressed (6 seconds by measurement from the tape recording log) to 380 mm Hg (15,000 ft) by lock and main chamber pressure equalization. The rescue team, which was located in the lock during all tests, entered the main chamber immediately upon equalization to render assistance. The subject was back on his feet quickly (a total of 25 seconds had elapsed), and the post-test

Figure 43. Altitude-pressure profile and skin temperature response
for altitude chamber experiment 2-4, Subject C.

SKIN TEMPERATURE—°C

ALTITUDE—ft x 1000

TIME—min

CHAMBER PRESSURE — mmHg

PRESSURE

ALTITUDE

"cool"

CALF (lost)
THIGH
MEAN
KIDNEY
CHEST
TRICEPS

88
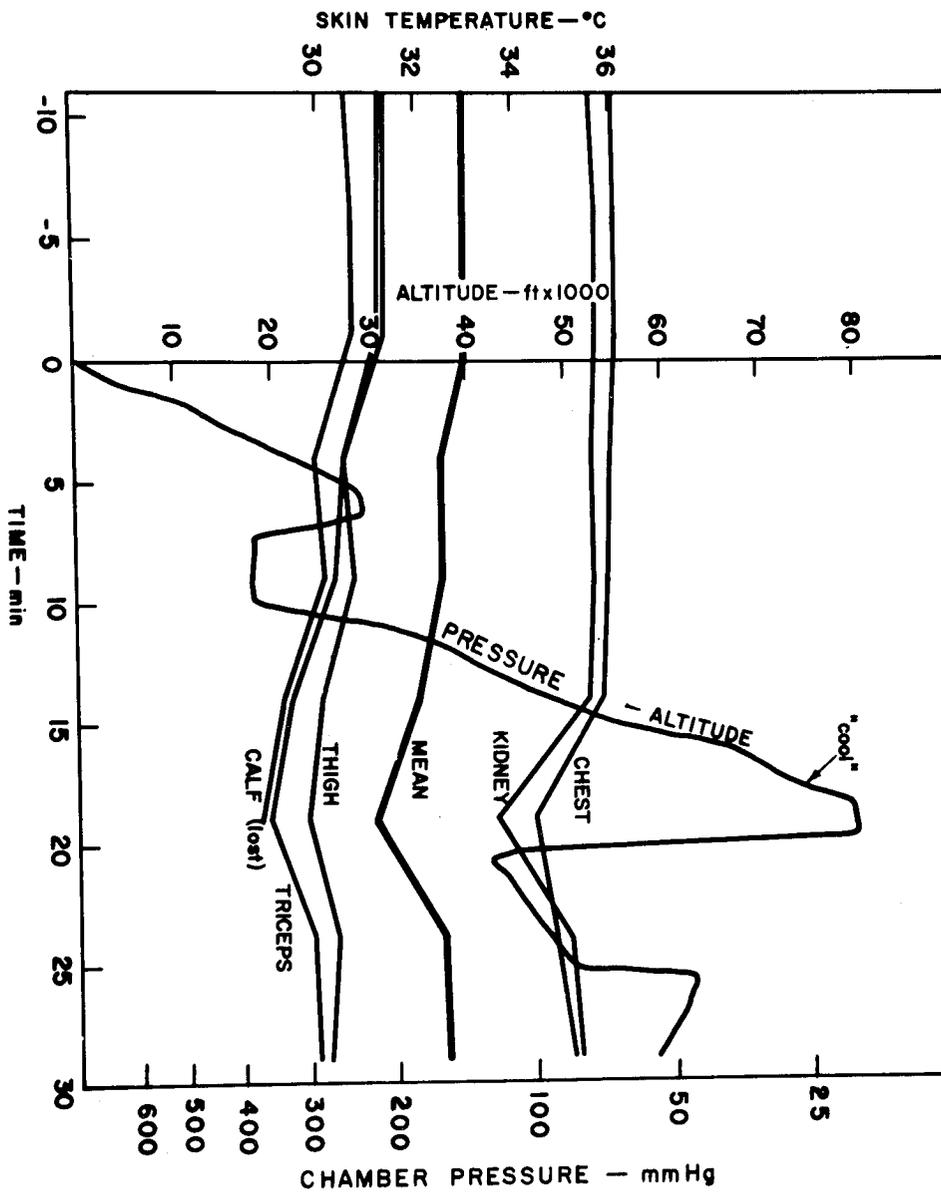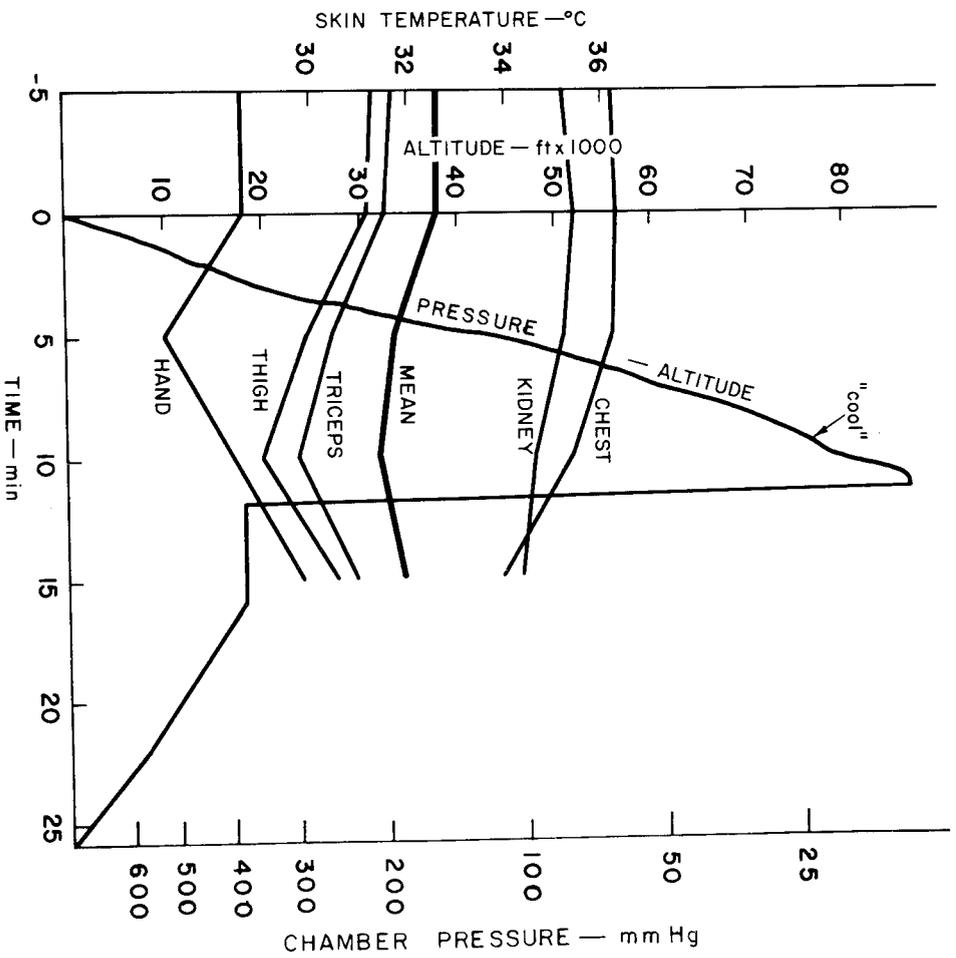
Figure 44. Altitude-pressure profile and skin temperature response for altitude chamber experiment 2-5, Subject C.

medical examination revealed no physical or physiological damage. A review of all of the data following the incident revealed that the syncope had resulted from a breathing system failure. A leak in the dome system of the high flow regulator produced faulty control and O_2 injection into the breathing system was limited. (This defect was, of course, repaired prior to the second phase tests. The CO_2 level apparently increased, and, combined with the amount of N_2 in the loop, reduced the pO_2 to hypoxic levels. The last inert gas measurements prior to the accident indicated an N_2 level of 10% and a CO_2 level of 0.2% in the breathing loop. With a total absolute pressure of 185 mm Hg (170 mm Hg breathing pressure plus 15 mm Hg for the diluent gases), the pO_2 should have been safe. The diluent gas sample was, however, collected while the subject was at a chamber pressure of 76 mm Hg (53,000 ft), approximately 5-1/2 minutes before subject syncope, and was being analyzed in the intervening period. An increasing trend in the level of diluent gases had not been detected, so the test was continued.

Results of other physiological tests performed with experiment 2-5 disclosed an arm volume change of 38 cc, or 33 cc/hr of pressure breathing, which is near the average for the laboratory tests. The leg did not show any change. A hematocrit increase of 2 vol% (44 to 46 vol%) was found, which may represent a fluid loss of only 5% of the blood volume (Ref. 5). The weight loss rate, hence water loss rate, averaged 185 gm/hr, which was higher than usually seen; some increase in evaporative (and diffusive) water loss while at reduced pressure may explain some of the increase.

Heat dissipation improved as expected when the chamber was evacuated. Skin temperatures during the altitude chamber runs were 2°C lower, on the average, than those observed during similar trials at ground level. The curves for mean skin temperature in Figures 43 and 44 show a downward trend with decreasing pressure. This suggests that what sweat the subject produced evaporated quickly and easily through the porous elastic mesh of the SAS garment.

Another observation underscored the freedom of evaporation of sweat in the near vacuum condition. During both tests, as the chamber was evacuated and the pressure fell past 25 mm Hg (approximately 76,000 ft equivalent altitude), the subject reported a sudden sensation of cooling on the torso and in the hands. Skin temperature data (see Figs. 43 and 44) confirmed the cooling effect. Notice in both low pressure runs the abrupt drop in the temperature of the chest and kidney regions when the chamber reached a pressure equivalent to 76,000 ft. These areas were covered with the impermeable material of the breathing bladder on the torso, and apparently some sweat had accumulated under these layers. When the ambient pressure was low enough, this sweat evaporated suddenly, a kind of flash boiling when the vapor pressure of the water became higher than the ambient pressure. The vapor pressure of water at 36°C, which was the measured skin temperature on the torso

during these experiments, is 42mm Hg. Allowing for the effect of mechanical pressure of the suit, when air pressure under the bladder became significantly lower than 42 mm Hg, boiling occurred, causing the sudden cooling sensation. Therefore we can expect that when the SAS is worn in the vacuum of space it will allow complete dissipation of metabolic heat through the well regulated physiological mechanism of sweating, even though some body areas are covered by impermeable materials.

Three more low pressure tests were made in the second phase. The PPBS was not carried by the subjects in any of the three experiments, nor were there any subject activities such as bicycling. Pressure-altitude profiles for the first two of these tests are presented in Figure 45.
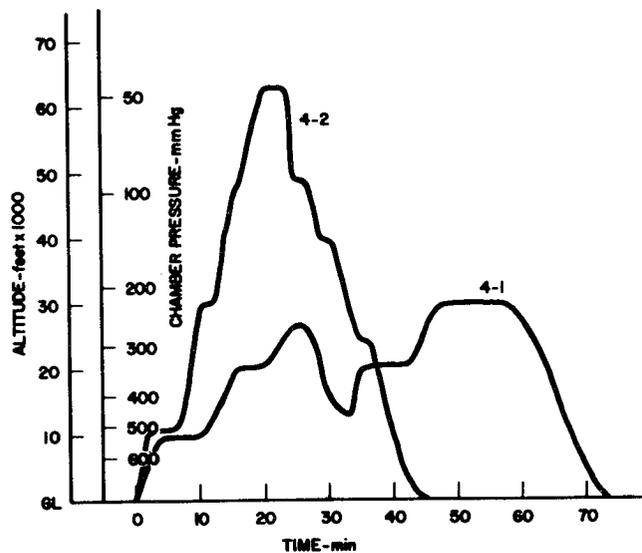
Figure 45. Altitude-pressure profiles for altitude chamber tests 4-1 and 4-2.

As in the earlier series, the initial test was performed on subject B and was for the purpose of equipment check-out and experimenter familiarization with the operation of new system components. The test lasted 73 minutes (GL to GL), and a minimum pressure of 226 mm Hg (30,000 ft) was reached. The secondary purpose for this preliminary test was to determine the most

efficient means to rid the breathing loop of N_2. Dump purging with the PPBS and careful bladder and helmet flushing with O_2 during donning did work satisfactorily as a minimum of less than 1% N_2 was obtained. The CO_2 level reached only 0.2% after more than an hour. Since only a partial garment assembly (parts of SAS #10) was worn by the subject, the breathing pressure was kept near the 100 mm Hg level throughout the experiment. The test was terminated as a safety precaution when the heart rate signal was lost due to outside interference on our telemetry transmitter's frequency.

The second experiment in this series was performed by Subject C (Fig. 45). As can be seen, an altitude of 63,000 ft (46 mm Hg) was reached during the test, which lasted 44 minutes. As in the previous run, this test was terminated when the subject's heart rate signal was lost due to a broken electrode lead wire. Breathing loop N_2 and CO_2 levels remained low, with maximum values of less than 1% N_2 and 0.20% CO_2. Skin temperatures showed no significant change, since low enough ambient pressures to cause rapid evaporation were not reached. Post-test limb volumes, hematocrit, and nude weight were not measured. The maximum heart rate level seen was lower for this subject than for comparable breathing pressures in the first phase altitude tests; however, a rate of 150 bpm with a breathing pressure of 180 mm Hg was recorded just before the signal was lost.

In the third test of this series, the altitude goal of 80,000 ft (20.9 mm Hg) was again reached by Subject C. Unfortunately this test had to be terminated after approximately 5 minutes at the target pressure because the subject developed a "bends" pain in his foot; this was 26 minutes into the test. The entire test lasted 42 minutes, and its pressure-altitude profile is presented in Figure 46.

Subject tachycardia was again observed, particularly at breathing pressures in excess of 150 mm Hg. Near the end of the test the heart rate average was 160 bpm with a breathing pressure of nearly 180 mm Hg. Loop N_2 levels remained low throughout (1% or less), but the CO_2 level did reach an all time high of 0.85%. As can be seen in Figure 46, the skin temperature decrease occurred as the subject passed through the 72,000 ft (33.5 mm Hg) mark. The water loss as measured by weight change was not significant, at an average of 30 gm/hr. Arm volume increase was 45 cc, or 26 cc/hr of positive pressure breathing.

In an attempt to determine whether the "bends" pain was due to a bubble or not, the chamber was repressurized from the 20.8 mm Hg level to 62 mm Hg for a short period. When the pain subsided at the higher ambient pressure, it appeared to be a pressure related problem, and the subject was returned to ground level. The development of a "bend" after nearly three hours of denitrogenation cannot be explained. The subject had no post-test sequelae.
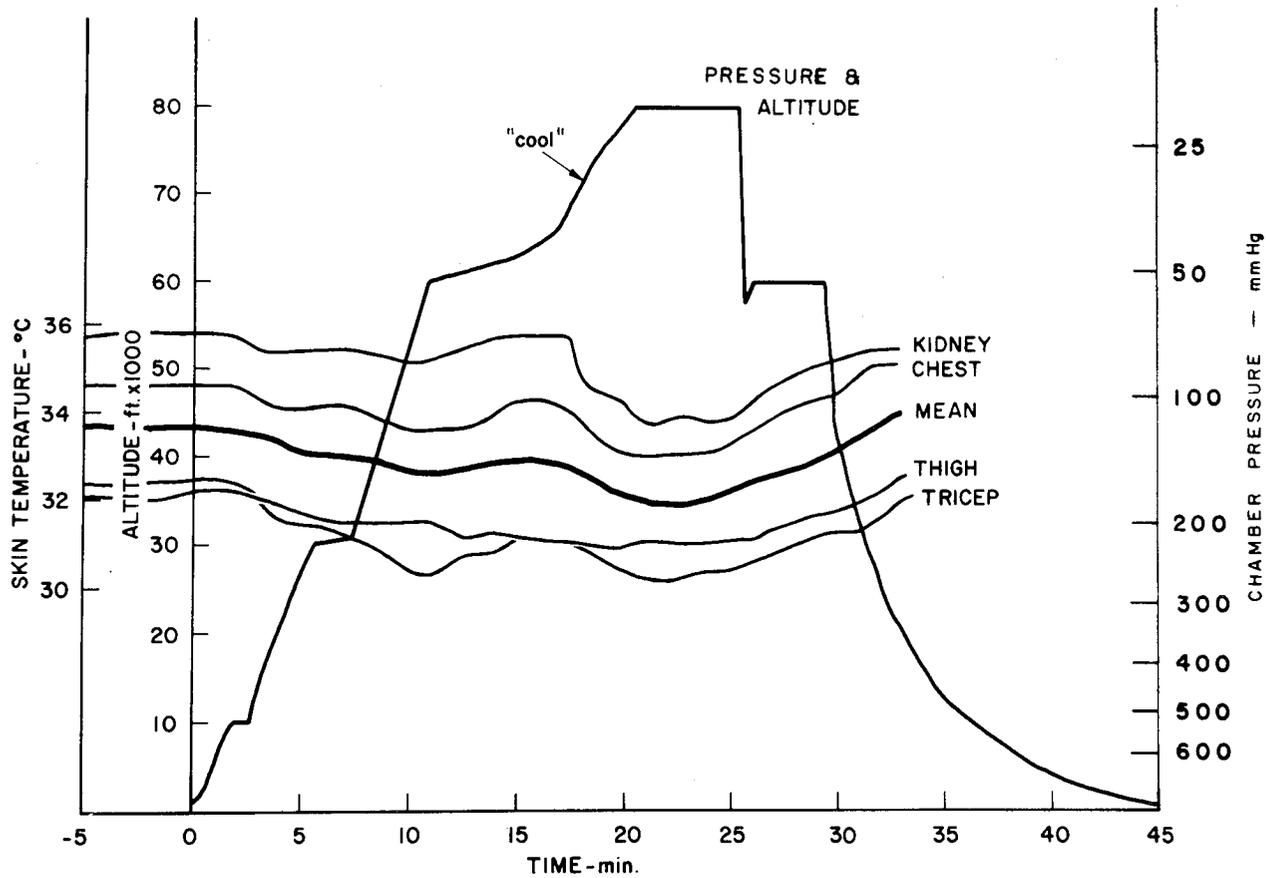
Figure 46. Altitude-pressure profile and skin temperature
response for altitude chamber test 4-3.

DISCUSSION

The principal aims of the development program were to produce a complete SAS system, verify its physiological soundness in the laboratory, and, finally, test its protective capabilities in an altitude chamber. In the laboratory one might have seen evidence of circulatory imbalances leading to syncope in a relatively short period of time at the breathing pressures tested. In the altitude chamber one might have observed gas formation under the skin, extremely high diffusive water loss, even freezing in the epidermis resulting from the rapid evaporation of moisture from the surface, or some other dermal problem related to excessive strain, drying, etc. None of these potential problems developed. And, most important, mobility, dexterity, and the energy cost of activity in the SAS were at least comparable, if not superior, to that obtained with recent full pressure suits.

We do not mean to imply that there are no problems remaining to be solved. Physiologically, varying amounts of tachycardia were observed on many occasions, particularly with one subject. The effect was directly related to the breathing pressure; however, it did not become troublesome until breathing pressures above 150 mm Hg were used. This effect undoubtedly resulted from blood pooling, which we were not able to detect with the techniques available to us. Pooling would result if the counterpressure supplied by the garments were significantly lower than the right heart pressure developed at a particular breathing pressure. The subject in this case would be breathing at positive pressures relative to the low counterpressure area, and responses similar to the syncope often observed in men wearing partial pressure suits while breathing at high pressures would be expected. The subjects in the SAS were much better off generally than men in partial pressure suits, since reduced counterpressures were restricted to isolated regions of the body and an entire body segment was never left unpressurized. The most difficult areas to pressurize occur where the limbs join the torso. A smooth transition of pressures across such regions would be necessary to prevent pooling.

The main area of pooling was thought to be in the capacitance vessels in the upper thigh and lower pelvis. Measurements of applied counterpressure in the thigh area showed that the regular bobbinet garments supplied only 25 to 30% of design pressures specified for that area; therefore in the second phase assembly (SAS #10) additional pressurization was obtained by the use of the powernet girdles and tightening of the bobbinet fabric. Breathing pressures in excess of 170 mm Hg were then better tolerated by the subjects.

How much offset in counterpressure could be tolerated, either above or below the breathing pressure, was not determined. No distinct relationship between gradient versus non-gradient garments and the amount of pooling was established.

The consistent small change in arm volume observed was always confined to the hands, where, due to the oval cross-sectional shape, pressurization was difficult to obtain with elastic materials alone. The custom molded rounding pads reduced the amount of fluid accumulation, but did not completely prevent it. The fluid was edematous in nature; return to normal hand volume routinely occurred within an hour or so after the test was completed. Some constriction of the vasculature in the shoulder area by the garments was suspected, and if present, aggravated the situation.

Pooling, as evidenced by increased heart rates, was the only physiological problem associated with wearing the SAS. Generally the skin showed no evidence of physical damage. Grating and scraping of the surface was minimal, and post-experiment examinations showed only some imprinting of seam lines and occasionally some pinching marks around joints. Petechiae were sometimes seen associated with the joint pinching; however, the damage was minimal and quickly cleared up. Cutting of the skin by the fabric threads was not a problem despite the amount of tension developed. Also, waffling of the skin by the fabric network was minimal even though the openings in the fabrics under tension were slightly greater than 1 mm^2. The sheer fabric used in the slip layer next to the body helped to limit this effect. Tests at low pressure didn't appear to worsen this potential problem.

The main problems with the SAS at the current level of development are mechanical rather than physiological. Indeed, the physiological problems observed probably would be solved in conjunction with solution of the mechanical aspects of suit design. Mobility, hence energy cost of activity, probably can be improved by the development of new elastic fabrics. A superior fabric should possess greater elongation, e. g. 200% or more, at a power equivalent to the powernet fabric developed for the present garments. Ideally, the fabric should allow two-way stretch without concomitant constriction at right angles to the stretched elements, i. e. without serious interaction. The mesh size should be less than 1 mm^2 when under full tension. Any non-elastic fibers used should possess fire retardant properties. In addition to Nomex, several other flame-resistant fibers such as polybenzimidazole (PBI) and Kynel^R (The Carborundum Co.) might be combined with various elastomers to form suitable elastic fabrics. Of the currently available elastomers, spandex is perhaps the best for vacuum exposure. The development of a new elastomer specifically for application in the SAS should be considered, although undoubtedly such development would be time consuming and expensive.

If fabric development is undertaken, a variety of fabrics each with a specific function should be created. For example, fabrics with elastic properties different from those of the basic torso garment fabric would be specified for the elbows, shoulder, hip, and knee joints. A biomechanical analysis of each joint's function would lead to the specification and application of a

given fabric. In order to simplify the problem of matching applied counter-pressures by differing adjacent fabrics, perhaps the entire limb segment of a given garment could be made of a single fabric. In order to accommodate changes in linear distance over joints with movement, the fabric would be oriented along the axis of maximum allowable stretch. In construction, the tailoring of each joint area should be performed individually in accordance with the properties of the selected fabric and the function of the joint.
A major goal of new fabric development would be to reduce the total number of individual garments required to reach the pressurization needed to breathe oxygen at more than 200 mm Hg.

The reduction in number of layers required is perhaps the most obvious way to reduce donning time. The current need for as many as six layers of fabric produced donning times far longer than desirable. A number of simple devices including pull rods, levers, and pulleys were tried during the development of the present SAS with limited success, and the development of a full body donning rig does not appear to be practical at this time. This is particularly true since the garments must be positioned precisely on the body in order for the engineered counterpressures to be applied. It is difficult to conceive of a single device or group of devices that could accomplish this task; however, each limb segment of the garment assembly could be expanded for donning by a series of detachable pneumatic expanders placed at appropriate intervals on the garment. After the garment had been carefully relaxed into position, the expansion devices would be removed. Since the fabric in this case could be in the form of closed cylinders, zippers or other closure devices would not be needed. The use of the torso pressurizing breathing bladder has already reduced the need for elastic fabric supplied counterpressure over the torso; hence donning and closure of this portion of the assembly would not be difficult using conventional techniques. The availability of elastic zippers and Velcro would improve both performance and closure in the present garments.

In conclusion, the SAS at its present stage of development will protect man from the effects of the vacuum environment, in a garment which permits improved mobility and natural body movements. Physiologically the approach is sound, and although there remain many problems to be solved, they are principally mechanical in nature. It has been suggested that solution of the mechanical problems, combined with careful tailoring based upon biomechanical analysis, plus the development of specific elastic fabrics, could eventually lead to a space qualified version of the SAS.

APPENDIX A--SUIT SPECIFICATIONS

SAS #1
Specifications for the First Prototype in a Series of SAS Garment Assemblies
100 mm Suit

Slip Layer. -- Snug white Lycra powernet applying 10 mm nominally, except on the torso, which may be less.

-- Full back zipper, with soft padded underlining, running from crease of buttocks to base of neck. This zipper should be light and flexible, possibly of nylon.

-- Arms end at small diameter of wrist below ulnar protrusion. Add a thumb loop.

--Legs end at ankle below tuberosities. Add stirrups.

--Neck ends with low turtle neck pattern.

--Minimize seaming and seam thickness.

1st Layer. -- Should apply 45 mm Hg. Low turtleneck at top.

-- Full front zipper from above symphisis pubis to top of neck. Two heavy cloth tunnels along zipper line to accept 1/2" rods.

-- End arms at finger crotches, legs at mid-foot.

-- Relief zipper on lower leg running from 1-1/2" above lower (ankle) margin to 1" below knee.

2nd Layer. -- Also should apply 45 mm Hg, and is similar to above, except:

a) zipper lines should not overlie; b) arms should end above elbow; c) legs should end above knee; d) no cloth tunnels along zipper line, but pull tabs of 2-inch wide heavy cloth, 4" apart along both sides of zipper lines; e)no leg or arm relief zippers.

--Applied pressure totals 100 mm Hg on torso.

--Applied pressure from shoulder to wrist decreases from 100 mm Hg to 60 mm Hg, approximately linearly.

--Applied pressure from hip-thigh joint to ankle decreases from 100 mm Hg to 60 mm Hg at ankle, approximately linearly.

Gloves. -- Should apply 50 mm Hg to fingers. Glove should extend to wrist line and overlap slightly. 60 mm transition at wrist.

Boots.-- Should apply 50 mm Hg, extend to ankle, transition to 60 mm Hg.

Breathing bladder. --Cut to pattern already made for subject. Sewn to outside of slip layer, attaching along top edge in front and bottom edges over hips (but not in center of abdomen and not in the back).

SAS #2: Second 100-mm Suit

General. -- Total applied pressure as in suit #1, i.e. 100 mm Hg on torso, gradient from 100 to 50 down each arm to hands and down legs to feet.

Slip Layer. -- As before, of white Lycra powernet. Padding will be sewn in under zipper, in crotch, in antecubital fossae, in axillae, post-malleolal fossae, and in popliteal spaces. Sleeves end in a palm cover with thumb hole. Legs end in complete foot covers.

1st Layer. -- Full suit of special heavy green-colored Lycra powernet. It covers legs, arms, and torso. Applied pressures are as follows: Feet-- 50 mm (to be matched with bootie overlap); ankles--60 mm; knee level--70mm; mid-thigh--80 mm; upper thigh--60 mm; hands 50 mm (glove overlap to be matched accordingly); wrist--60 mm; elbow level--70 mm; mid upper arm-- 80 mm; top of upper arm--60 mm; torso--25 mm. Special treatment at knees and elbows: an ovoid piece of material to be cut out of the flexor surface of elbow and knee and re-seamed, so that the arm and knee joints of the suits are neither stretched nor pinched in mid-flexion. Sleeves end in a palm cover with thumb hole, whereas the legs end around the arch of the foot. Full and separate leg and arm zippers will be supplied. The torso will be closed with a full back zipper. Cloth tunnels will be placed alongside of the back zipper, and shall accept metal bars measuring 1/4 x 1/2" in cross section. The cloth tunnels should be interrupted three times to allow insertion of the bars in segments of the tunnels.

2nd Layer. -- A dual-layer torso garment with short arms and legs, made of a tape layer and an overlayer of special heavy green-colored Lycra powernet (see sketch). The outer layer applies 25 mm Hg to the torso and a gradient from 40 to 25 m in upper arms and thighs (25 distal end, 40 proximal end). This garment closes with a front zipper, running from the symphisis pubis to the neck.

The inner layer covers the torso only. It is made of material which is continuous in back, attached to the overlayer, and split into 3-inch tapes in front (see sketch). The tapes end in Velcro material over the final 4 inches. Velcro tape will be selected to withstand the shear force. On the top tape of each pair, a sturdy hand loop is attached to aid in closure. The hoop tape of Velcro should face away from the body. The pressure applied by the tape layer shall be calculated to supply approximately 50 mm Hg. (Final applied pressure is adjustable by moving the Velcro closure.)

Accessory Layer. -- A torso garment with side zippers applying 30 mm to chest and abdomen. Top ends in low turtleneck. Bottom ends in a 4" wide crotch strap which is continuous with the back of the garment and attaches to the front after donning. The strap does not stretch significantly when attached.

SAS Second 100-mm Suit

Dual-Layer Garment

zipper (outer)

Reinforcement

3" strip tape
in place

Velcro patch
(pile tape)

Velcro patch
(hook tape)
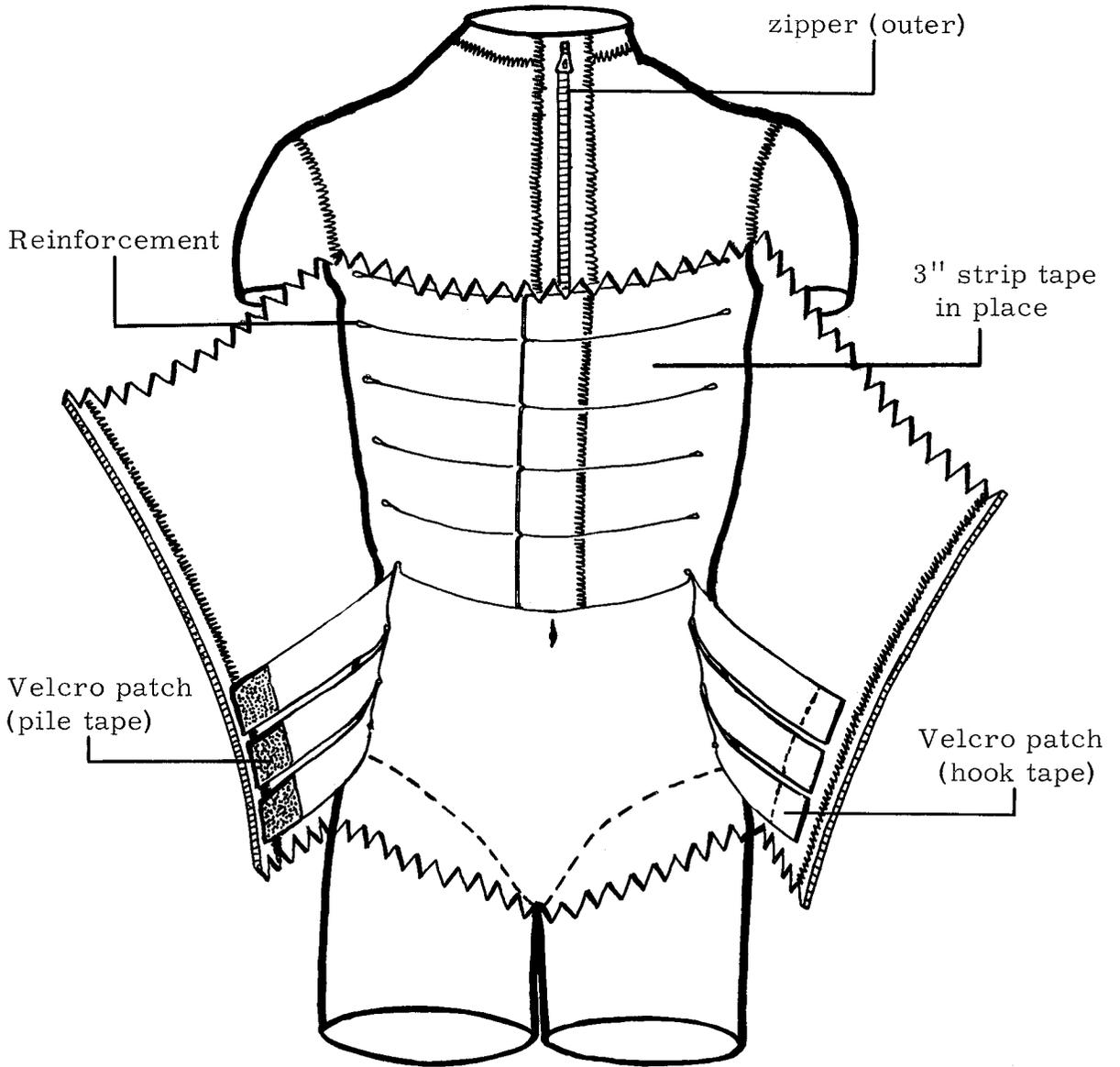
Arm holes are cut away from the shoulders, as in a vest.

Booties and gloves. -- They will be supplied to furnish up to 50 mm pressurization of hands and feet, and mated to garment overlap areas. The index finger and thumb of the glove will have no seams running around the tip. A 3/4"thick unicellular foam pad, tapered at the edges, will be sewn into the glove to cover the dorsum of the hand.

Neck endings. -- They will be of low turtle neck design, ending in a 2" band of elastic tape. All garment overlap areas shall be pre-designed to produce the total selected counterpressure in as smooth as possible a fashion.

Breathing bladder. -- Attaches to slip layer. It shall be made of impermeable stretch material (Reeves). Otherwise the design is the same as in Suit #1. All adhesives used must be compatible with a 100% oxygen atmosphere in the bladder.

SAS #3: First 170-mm Suit

General. -- The third garment shall apply a total of 170 mm Hg counterpressure to the torso and a gradient from 170 mm Hg proximal down to 120 mm Hg distal on the limbs. This shall be accomplished with four full body garments designed to deliver the composite pressures described. All garment layers and accessories (when pertinent) shall have markings to indicate anatomical reference points to assist in positioning the garment properly. In addition, each component shall bear a label which codes the item to the particular garment: i.e. 3 (SAS #)--2 (layer #)--50 (counterpressure). Garment accessory components are the gloves, booties, and breathing bag. Details of each of the components are outlined in the sections that follow.

Slip Layer. -- As in SAS #2, with the following exceptions: a) single back zipper shall be a medium sized nylon type, extending from the level of the vertebra prominens to the first lumbar region. The neck of the slip layer will be closed and composed of a 1-1/2" to 2" anti-roll band. Padding as before will extend from the level of the 5th lumbar to the base of the neck band; b) special bioinstrumentation facilities to be added are padded pouches for thermistors and padded patches for ECG electrodes. The thermistor pouches are circular, 1" in diameter, and contain 1/16" thick open cell foam with a 3/16" center well open to the skin, and an opening for insertion of the thermistor. The cross-sectional appearance should be as in the sketch on the next page. A total of five pouches are to be constructed, in the following locations: a) left--mid-center gastrocnemius; right--mid-center anterior quadriceps femoris; left--kidney area; right--pectoral, midway between sternum and axilla; right--mid-center triceps. The electrode patches are to be 1" square

foam-containing pads with a small center opening (approximately 1/8" in diameter) for wire leads. These are to be located over the manubrium and left precordium (mid-lateral region of the 5th intercostal space).
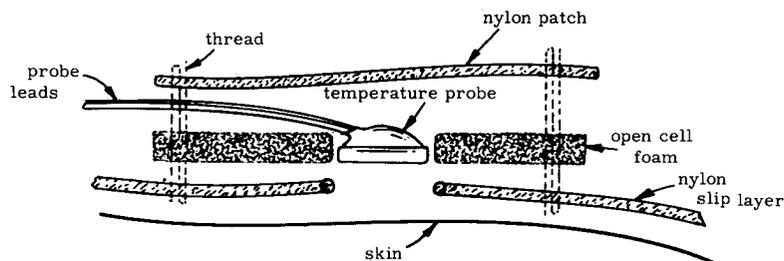
1st Layer. -- To deliver 35 mm Hg to the torso and a limb gradient from 40 mm Hg distal to 35 mm Hg proximal. To be constructed of Jobst bobbinet fabric with zippers as in SAS #2 full body garment layer. The neck portion is to end in a low turtle neck composed of the anti-roll band elastic material. Special treatment as follows: a) instrumentation lead slits are to overlie the entry port positions in the slip layer; slits are to be approximately 1/2" in length and constructed so as not to gape when garment is under tension; b) limb joint areas, i.e. knee and elbow, are to contain sized ovoid inserts of bobbinet fabric on both the flexor and extensor surfaces in which the elastic fibers run longitudinally rather than circumferentially. These are to be engineered so that the calculated pressure may be applied when the particular joint is at mid-range position. Care should be taken to insure that the extensor insert is not fully elongated before the joint is fully flexed; c) shoulder and axillary treatment involves the orientation of the elastic core fibers on custom fitted insets while retaining, insofar as is possible, the specified counterpressure. The sketch on the next page depicts basic design approach, with the arrows showing the direction of the elastic fibers and the dashed lines showing the seams; d) axillary fitted pouches constructed of the rubberized elastic fabric (Reeves) are to be made; they are to be sealed except for one small opening tube of plastic which must ultimately be collapsed and
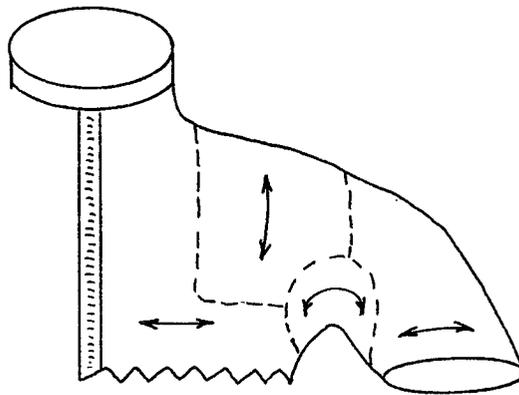
heat sealed by Webb Associates; e) all zipper seam lines for this layer and all successive layers are to incorporate firmly attached nylon fabric tunnel loops which are sized to receive 1-1/2" long x 5/32" diameter pull rings. Spacing between the tunnels is to be approximately 3/4" and mating tunnels on either side of the zipper are exactly opposite. Tunnels are to begin approximately 1" above the position of the zipper slide when unzipped and run the entire length of the zipper. The sketch below shows the basic construction detail:

3/4"

1-1/2"

nylon fabric tunnels

approximately 1/4" dia.
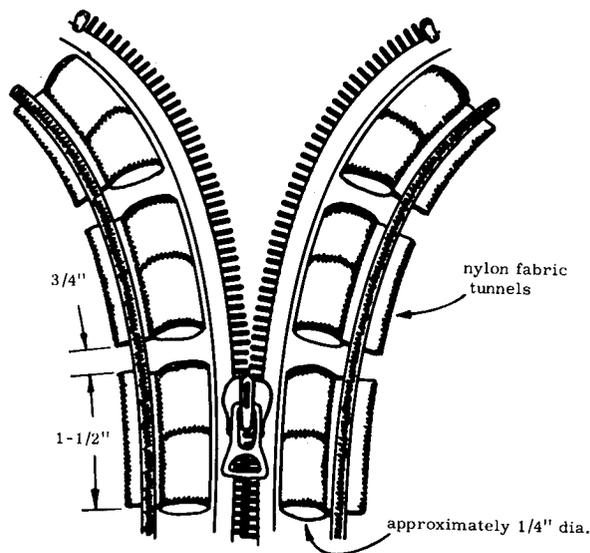
2nd Layer. -- Also a full body garment designed to deliver 50 mm on the torso and in gradient fashion from 60 mm distal to 50 mm proximal on the limbs. Torso to be constructed of powernet fabric and limbs of bobbinet. The counterpressure is to be equal at the fabric juncture. Zippers are to be the same as in the first layer, but not overlapping. Sleeves and legs end at the wrist and ankle and are provided with anti-roll bands and retainer straps around the thumb and arch respectively. Special joint treatment and zipper tunnel loops are to be the same as in layer #1. A sewn eyelet (buttonhole) approximately 1/4" in diameter should be placed near the base of the front torso zipper. The neck area shall be of a "scoop neck design," extending to approximately 1" from the base of the subject's neck.

3rd Layer. -- A full body garment much as above, except that the limb gradient is from 30 mm distal to 50 mm proximal. Zipper positions are generally the same, but not overlapping.

4th Layer. -- A full body garment entirely of the bobbinet fabric designed to deliver 35 mm to the torso and a gradient from 3 mm distal to 35 mm proximal. Joint treatment same as in above layers. A single front torso zipper (which is displaced so as not to overlap underlying zippers) is the only opening. The sleeves and legs end in anti-roll bands at the wrist and ankles, which are engineered to smooth the gradient continuum when the gloves and booties are on.

Special torso garment. -- This garment is to be a basic torso garment with a single front zipper and short sleeves and legs so that when matched with layers #2 and #3 it will allow testing at essentially 100 mm Hg. The material used will be powernet, and the neck will be the "scoop neck" design. The axillary portion of the sleeve attachment may be left open at this time.

Gloves. -- Two sets of gloves will be furnished. One pair is to be used during the donning process and will supply 50 mm to the fingers and approximately 40 mm to the remainder of the hand. The material will be bobbinet. The second pair will supply 120 mm beginning at the finger tip and reducing in gradient fashion to produce the proper counterpressure on the hand when mated with the hand portions of the full body layers. The back of each glove (dorsum) will contain a foam pad sized to the back of the hand to assist in distribution of the hoop tensional forces. The thumb and index fingers (at least) will be so constructed as to leave the tip free of a seam line.

Booties. -- Two pairs of booties will be furnished. Each is to supply approximately 60 mm Hg and may be constructed of the powernet fabric. Again, overlapping areas with full body layer "hold downs" on the foot must be taken into account in calculating counterpressures to be delivered by the booties. Foam pads, sized to fit the post-malleolar depressions, shall be sewn into one pair.

SAS #3 -- Layers #1, #2, #6
Bobbinet Limbs, Powernet Torso, Full Body Garment

turtle neck on #1 only

(scoop neck on #2 & #6)

axillary patch with tuck

zippers #2, approx. 6" each   42   35*

35

flexor tuck   40

elbow patch; cords run longitudinally   50

pull loops to fit 1-1/2" buckles-- 3/4" between

#1 sleeves end with gauntlet and thumblet

#2 & #6 end at wrist with 1" antiroll band and thumb strap

50

zipper approx. 10 1/2"

#2 zipper on limbs

(zippers do not overlap on) #1 with #2

move torso zippers 1" to right or left of midline of layer #2

layer #3 to opposite by 1"

#2 zipper approx. 12"

*numbers refer to counterpressure in mm Hg

knee patch-- core vertical

knee bend tuck

#2 &#6 end at ankle with antiroll band and arch holding strap

ankle tuck

#1 ends at arch with footlet

1/2 leg bobbinet, torso powernet, no arms

scoop neck

bobbinet inset, core
run over shoulder

35*

zipper offset
approx. 1" to side
of midline
opposite #2

pull tunnels as in
layer #2

35

30

10" #2 zipper

1/2 leg ends in
antiroll band 1" or
more wide (not
interrupted by zipper)

*numbers refer to
counterpressure
in mm Hg

104
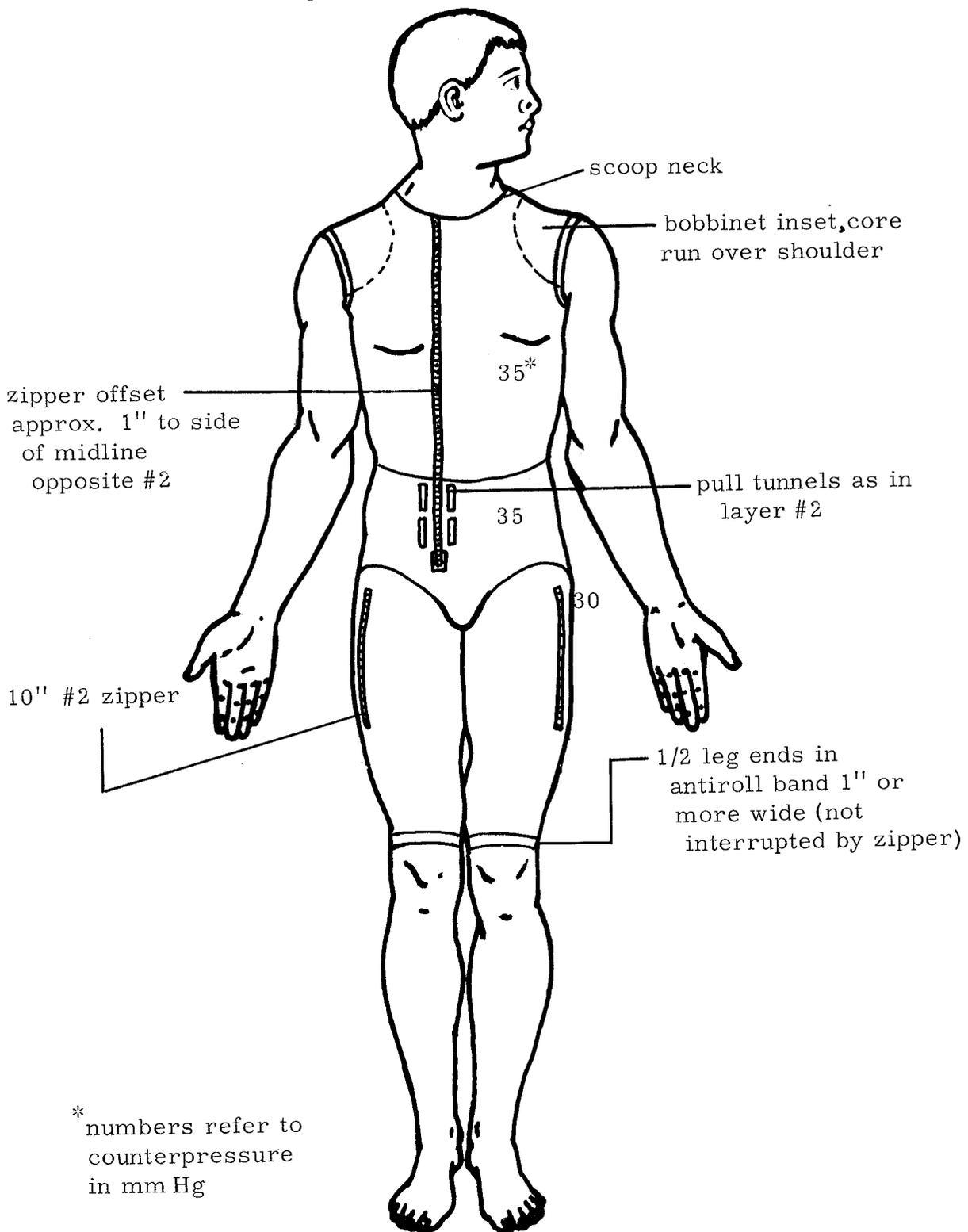
SAS # 3 -- All Bobbinet
1/2 arms; full legs -- Layer #4

scoop neck

45*

core

zipper 8" long #4
not overlapping layer
#2

sleeve ends above
elbow in 1" anti-
roll band

40

axillary tuck

zipper offset from
#3 -- no tunnels

30

#2 zipper
approx. 10"
long

21

knee patch
on anterior surface

knee bend tuck
on posterior surface

40

#2 zipper approx. 12" long

legs end at ankle
in 1" antiroll band;
has ankle holddown strap

35

*numbers refer to
counterpressure in mm Hg

105

SAS # 3 -- Layer # 5
all bobbinet, 1/2 legs, no arms

core direction

zipper offset from
one on layer #4
(no tunnels)

15*

30

10-1/2" long
#2 zipper--not
overlapping one
on layer #4

legs end with
antiroll band

26

(Note: Velcro patches
may be used for hold-
down; must be matched
for position to
layer #4)

*numbers refer to counter-
pressure in mm Hg
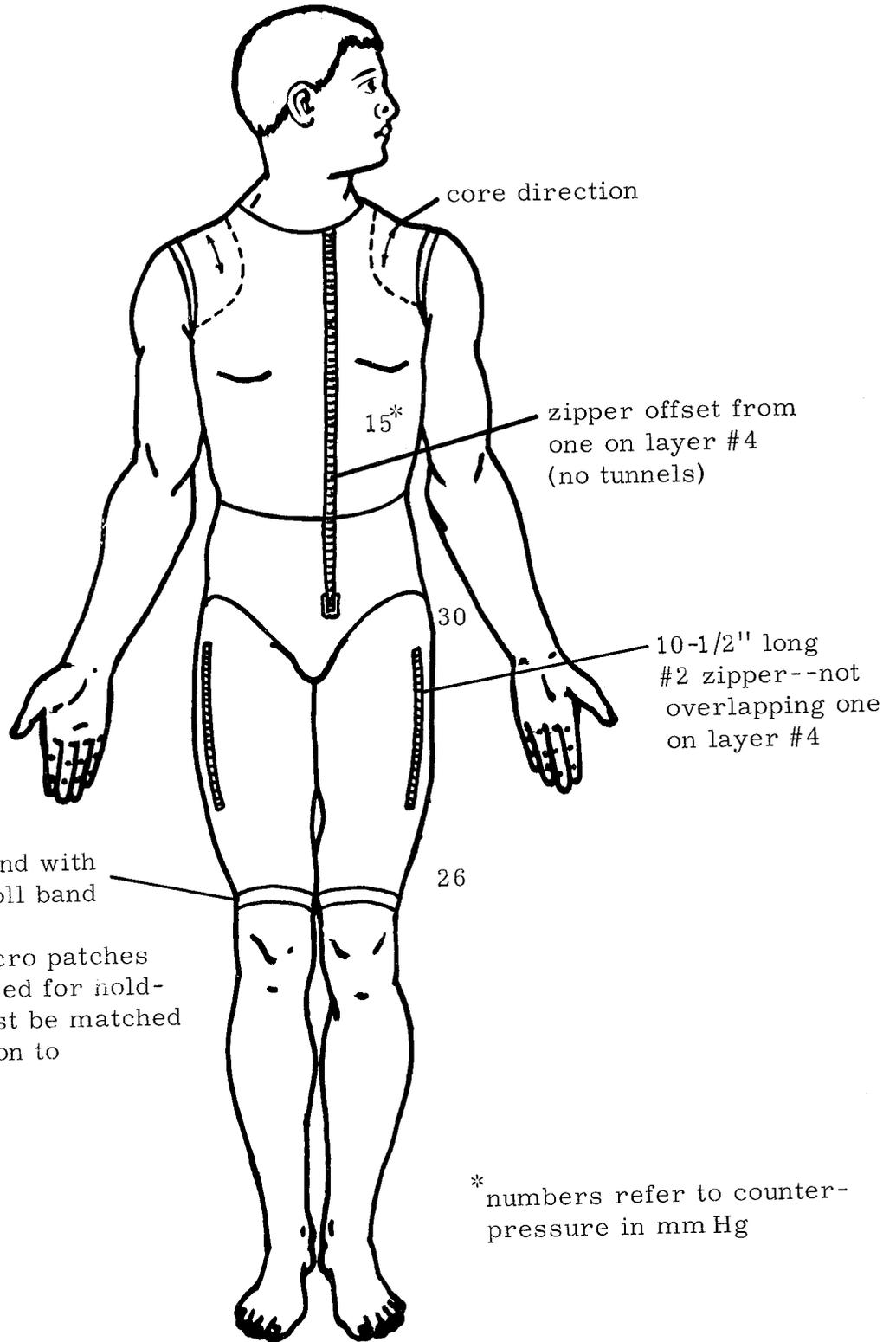
<u>Breathing bladder.</u>-- Following the design specified earlier, a breathing bladder will be furnished which is constructed of rubberized stretch material (Reeves). The outside border shall have strategically placed nylon (or other non-stretch material) tabs to facilitate anchoring the bladder to the slip layer. All adhesives used will be compatible with 100% O_2. Fittings for the bag inlet and outlet will be furnished by Webb Associates.

SAS #4 - #7: 100 mm Hg and 170 mm Hg Suits

The following paragraphs describe the construction details for the fourth in a prototype proving series of SAS garments. Three garments are to be tailored to fit each of three subjects and shall be called garments #4, #5, and #6. The complete garment assembly in each case is to apply a total of 170 mm Hg counterpressure; however, the layers are so designed that the garment can be worn as a 100 mm Hg test garment. At each pressure level the maximum allowable gradient from point to point on the body will be 25 mm Hg. In addition each layer of each garment shall be numbered in a sequence, so that donning an individual layer does not exceed the gradient limit. Generally the distal limb segments will be at the higher pressure when compared to the torso. In no case shall the design pressure of a given layer be such that the required stretch in the material upon donning be more than 60% of the total elongation potential. Also all limb segments will be fabricated of the Jobst bobbinet material (Lycra core, if available), and the strong green Lycra powernet fabric will be reserved for use on the torso only.

The only major change from SAS #3 involves the construction of a special foundation garment. This garment is a composite and is to be made up of the slip layer, breathing bladder, and an outer bobbinet layer. Garment layers donned after the base layer are called power layers and are numbered consecutively (PL-1 through PL-5).

<u>Foundation garment assembly--slip layer.</u> -- As with SAS #3, the slip layer will be a full body garment constructed of fine mesh, white, Lycra-nylon powernet material. The counterpressure applied will be minimal and not additive to the total suit assembly. This garment will contain the special bioinstrumentation pockets as outlined for SAS #3 and positioned as shown in the drawing called "slip layer foundation garment" (next page). The garment has an entry zipper sewn to include the other components of the base layer. The neck is of the "scoop" design and sized to fit at the base of the neck. The garment will contain footlets; however, the sleeves are to end in 1" anti-roll elastic bands at the wrist. Special treatment over the limb joints (elbow and knee) includes the following:
   a) flexor surface--a liner of approximately 0.015" thick natural gum rubber covered by a 1/8" thick open cell foam is sewn so that in the neutral

Part I--Slip Layer
Foundation Garment

scoop neck

axillary shoulder
treatment (see text)

electrode cable
formation point

thermistor pouch
(see also #2, 3, 4, 5)

extensor surface patch

flexor surface pad
(see text)

thermistor cable
formation point

EKG electrode
patch (see also A & C)

opening-rectal
probe (backside)

pelvic pad

antiroll
band

flexor surface pad
(see text)

extensor surface patch
(see text)

full foot cover
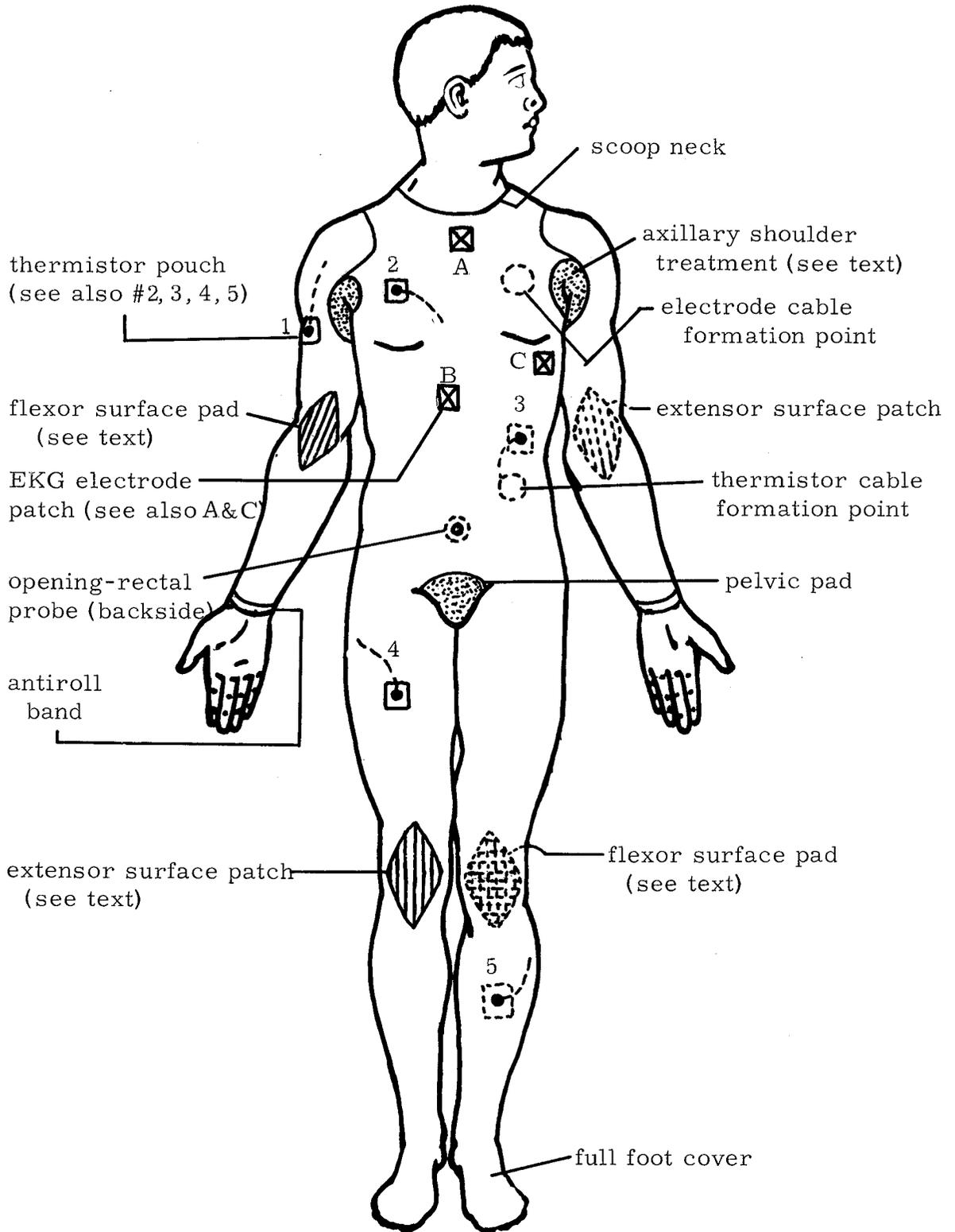
condition the garment segment assumes approximately a 15° angle at the joint. Any extra slip layer material which accumulates will be removed and the opening resewn.

b) extensor surface--an ovoid section of material over the joint area is to be removed and replaced by similar material in which the core fibers run longitudinally rather than circumferentially. The size of the insert is such that a slight stretch is needed to obtain the 15° of flexion produced by (a) above.

Treatment of the axillary (and shoulder) area shall be the same as that incorporated in SAS #3 except the foam pad inserts will have an inner liner of gum rubber. The entire pad shall be sewn in place. The thermistors and all lead wires are to be furnished by Webb Associates and will be installed in place before unitizing the three components of the combination base-layer assembly. A small round buttonhole opening (1/4" diameter) will be placed in the rear of this garment and all over-layers for the passage of the rectal probe lead wire. The holes should overlap in all layers and be located on the midline at the top of the groove produced by the gluteal masses.

Breathing bladder. -- The breathing bladder is to be constructed as shown in the two drawings on the next two pages (breathing bladder, front and rear views). The bladder will be fabricated for two of the garment assemblies from rubberized nylon material and from the rubberized elastic material (Reeves, style 2612) for the third. Once formed and sealed, the bladder is sewn in position to the outer surface of the slip layer. Later the bladder is sandwiched between the slip layer and the outer foundation layer and resewn to both layers. The single 1-1/4" diameter entry port is located on the right lower back portion of the bladder approximately 20" below the base of the neck and 4" to the right of the spine. The exact position will be determined at the time of fitting for each subject in order to match the PPBS backpack in position on that subject. The entry port fitting will be supplied by Webb Associates.

Outer foundation layer. -- The outer layer of the foundation garment assembly is a full body garment of bobbinet. This layer is to apply 15 mm Hg counterpressure to the torso and not more than 30 mm Hg distally on the limbs. Joint treatment and design are as shown in the drawings labeled "outer layer foundation garment, front and rear view." A special instrumentation pocket insert measuring 1-1/2" square is to be positioned over the mid-bicepital groove on the left upper arm. The pocket may be a simple invagination in the bobbinet material containing a thin 1/8" thick foam pad and left open on the front edge.

The sleeves should end in a gauntlet which has a thumb opening and finger openings with crotch straps. The legs end at the arch of the foot in a half foot cover. Excess material on the anterior ankle joint line is to be removed from both layers and resewn so that the neutral garment position is nearly a right angle at this point.

Foundation Garment -- Part 2 -- Breathing Bladder*
Front View

seal and seam

bladder
(ubberized
nylon or
elastic)

open area

umbilicus

seal (not attached)

* to be sewn in place to the
outer surface of the slip
layer and subsequently
sandwiched by the outer
foundation garment
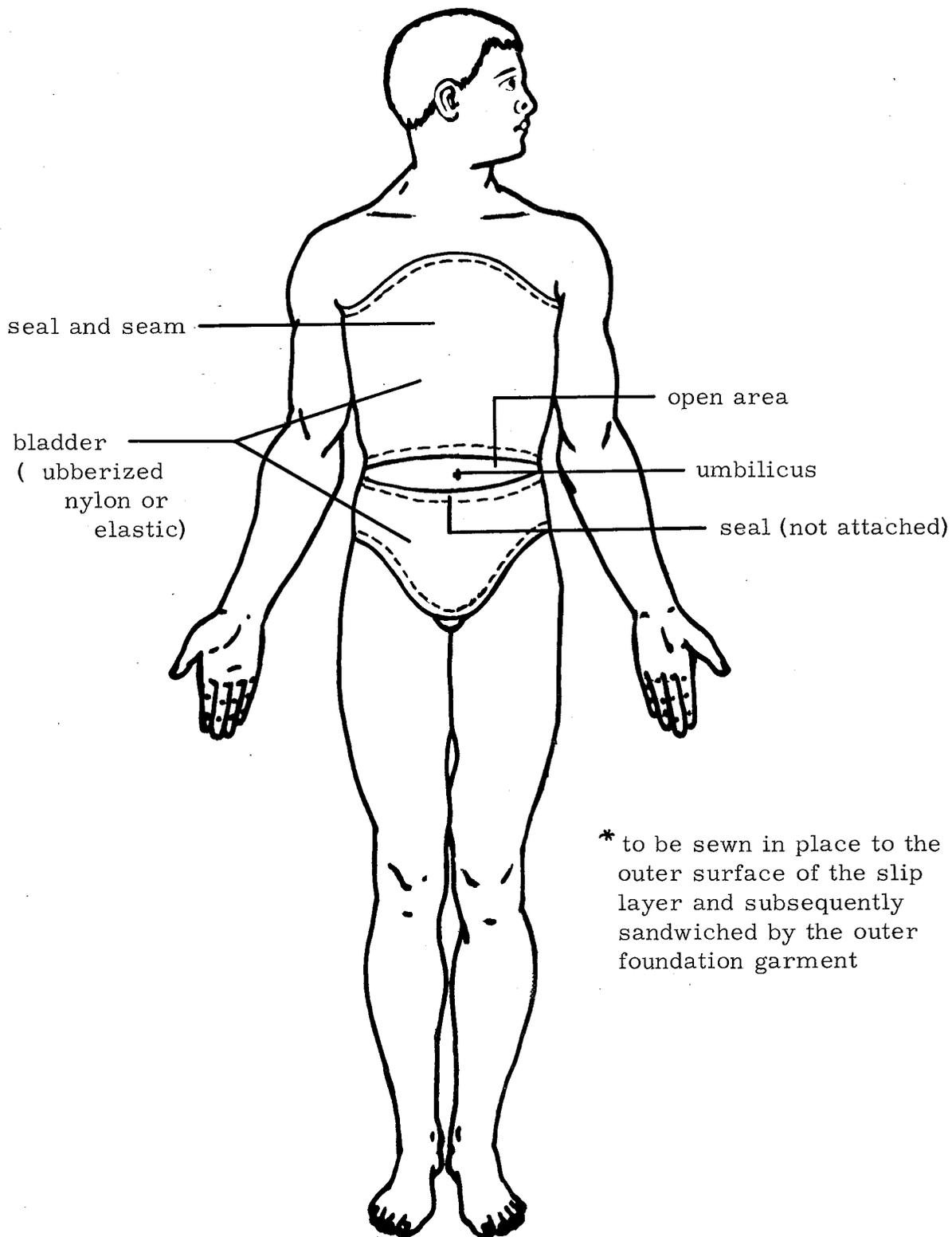
Foundation Garment--Part 2--Breathing Bladder

Rear View

bladder

extension of
open area

seam and
seal line

inlet port
fitting
1-1/4" dia.

Part 3 -- Outer Layer
Foundation Garment

Front View

1" antiroll band

axillary shoulder
treatment--see
SAS #3

opening for EKG leads

pocket for insertion of
blood pressure sensor

flexor surface
cut-out

gauntlet with
thumb cut-out

thigh zipper

knee extensor patch

half footcover

ankle cut-out

Part 3--Outer Layer
Foundation Garment

neck antiroll band

axillary-shoulder
treatment

midline zipper
and spinal pad--
to include slip layer

elbow extensor patch

thermistor lead
cable opening

breathing
bladder fitting
opening

rectal probe
pass-through

gauntlet--with
finger crotch
straps and thumb
hole

reinforced zipper base

knee flexor
cut-out

post-malleolar pad

Four openings must be made in this layer and all overlayers to serve as pass-throughs for instrumentation cables and the breathing bladder fitting. The location of the bladder fitting and rectal probe openings have been described. One opening for a bioinstrumentation cable will be on the left lower back directly opposite the breathing bladder fitting opening. The second cable opening will be positioned on the left upper chest on line with and approximately 2" above the nipple. All openings will be stitched like buttonholes to prevent raveling. The bladder opening will accommodate a 1-1/4" fitting and the cable openings will be circular with a diameter of approximately 1/2".

Once fabricated this layer is pulled over the slip layer-breathing bladder combination, carefully positioned, and both garment layers are cut along the rear midline for the attachment of the entry zipper. The zipper should be approximately 20" long and sewn to include both garment layers. The bottom of the zipper should extend to lie over the 4th lumbar spine. A spinal depression pad of encased (fine mesh powernet material) open-cell foam shall be included and attached to lie under the zipper line. Sewn attachment points to maintain layer positioning may be added as necessary. Limb zippers are to be inserted to include both layers only on the lateral surface of the thigh area of each leg. A thin, smooth backing for this zipper must be included to prevent traumatizing the bare skin. These zippers should be approximately 12" long. The entire assembly should be as easy as possible to don.

Power Layers. -- Five power layers (PL 1 through PL 5) will be needed to develop the required 170 mm Hg counterpressure for each total SAS assembly. The design of these layers is shown in the drawings labeled "power layers--basic design, front and rear views." They will be similar in detail to the SAS #3 power layers, i.e. the use of powernet is reserved for the torso, dual limb zippers, special joint treatment, etc. The size of the scoop neck opening will be specified at the time of fitting to match the helmet breastplate size. Power layers #2 and #5 will have a tunnel of non-elastic material approximately 1/2" in diameter attached firmly to the neck of the garment. Buttonhole slits will be made in the outer surface of the tunnel approximately 1" apart on either side of the front midline for the insertion of a draw cord. Webb Associates will select the draw cord. The size must be such that when constricted (without wrinkles) with the draw cord the tunnel will fit firmly on the circumference of 24-1/2".

Except for PL#2 and #5, all layers may end in the sleeves with a 1" wide elastic anti-roll band at the wrist and on the legs with a similar band positioned just above the ankle joint. Layers #3 and #5 are to include hand gauntlets and half foot covers as described for the bobbinet foundation layer.

The counterpressures to be developed by each layer for the various body areas are shown in the drawing on page 117. As can be seen, PL#3

Power Layers--Basic Design
Front View

non-stretch nylon tunnel
added to PL#2 and PL#5

axillary-shoulder
treatment

EKG cable pass-through
(all layers)

limb zippers

flexor cut-out

nylon closure
tunnels (see
SAS #3 specs)

mid-zipper (not to
overlie in
successive layers)

zipper base
reinforcement

antiroll band
(except on PL#2
and PL#5)

powernet
end-point

limb zippers (#2)

extensor patch

antiroll band
(except on PL#2 & #5)

Power Layers--Basic Design

see front view

axillary cut-out
and patch

see front view

extensor patch

breathing
bladder
pass-through
(all layers)

thermistor cable
pass-through
(all layers)

rectal probe
pass-through
(all layers)

flexor cut-out

antiroll band

Layer Counterpressure by Areas of the Body

FG--15 mm Hg
PL1--35 mm Hg
PL2--35 mm Hg
PL3--15 mmHg
PL4--35 mmHg
PL5--35 mmHg

upper arm:

FG--20 mm Hg
PL1--30 mm Hg
PL2--50 mm Hg
PL3--none
PL4--35 mm Hg
PL5--35 mm Hg

lower arm:

FG--30 mm Hg
PL1--40 mm Hg
PL2--30 mm Hg
PL3--none
PL4--50 mm Hg
PL5--20 mm Hg

upper leg:

FG--20 mm Hg
PL1--30 mm Hg
PL2--30 mm Hg
PL3--20 mm Hg
PL4--30 mm Hg
PL5--40 mm Hg

lower leg:

FG--30 mm Hg
PL1--40 mm Hg
PL2--30 mm Hg
PL3--none
PL4--50 mm Hg
PL5--20 mm Hg

Note:

distal-proximal gradients to
match area counterpressures;
design goal to ±5 mm Hg.
Limb distal counterpressures
may be reduced--not to ex-
ceed a total accumulative
gradient difference more
than 25 mm Hg.

completes the 100 mm Hg assembly and is an armless torso garment with half legs and is fabricated of bobbinet. All layers which require powernet on the torso will be supplied with heavy nylon closure tunnels sewn in with the front zipper. The design and location of these tunnels is as used in SAS #3. Extra strength thread and extra stitching will be used for reinforcing zipper bases and closure tunnels to prevent ripping during donning. Special attention must be paid to sleeve and ankle endings so that overlapping discontinuities will not result in tourniquet effects as layers are added. In addition, care will be taken to insure zipper placement in successive layers so that they will not be directly on top of one another.

Gloves and footcovers. --Two sets of bobbinet gloves will be supplied with each garment. One pair should be engineered to be worn with the 100 mm Hg assembly and the other with the full suit. These gloves will be of a special design, the patterns for which will be supplied by Webb Associates at the time of subject fitting. Briefly, the design is such as to minimize the seaming on the finger tips. A pouch covering the dorsal su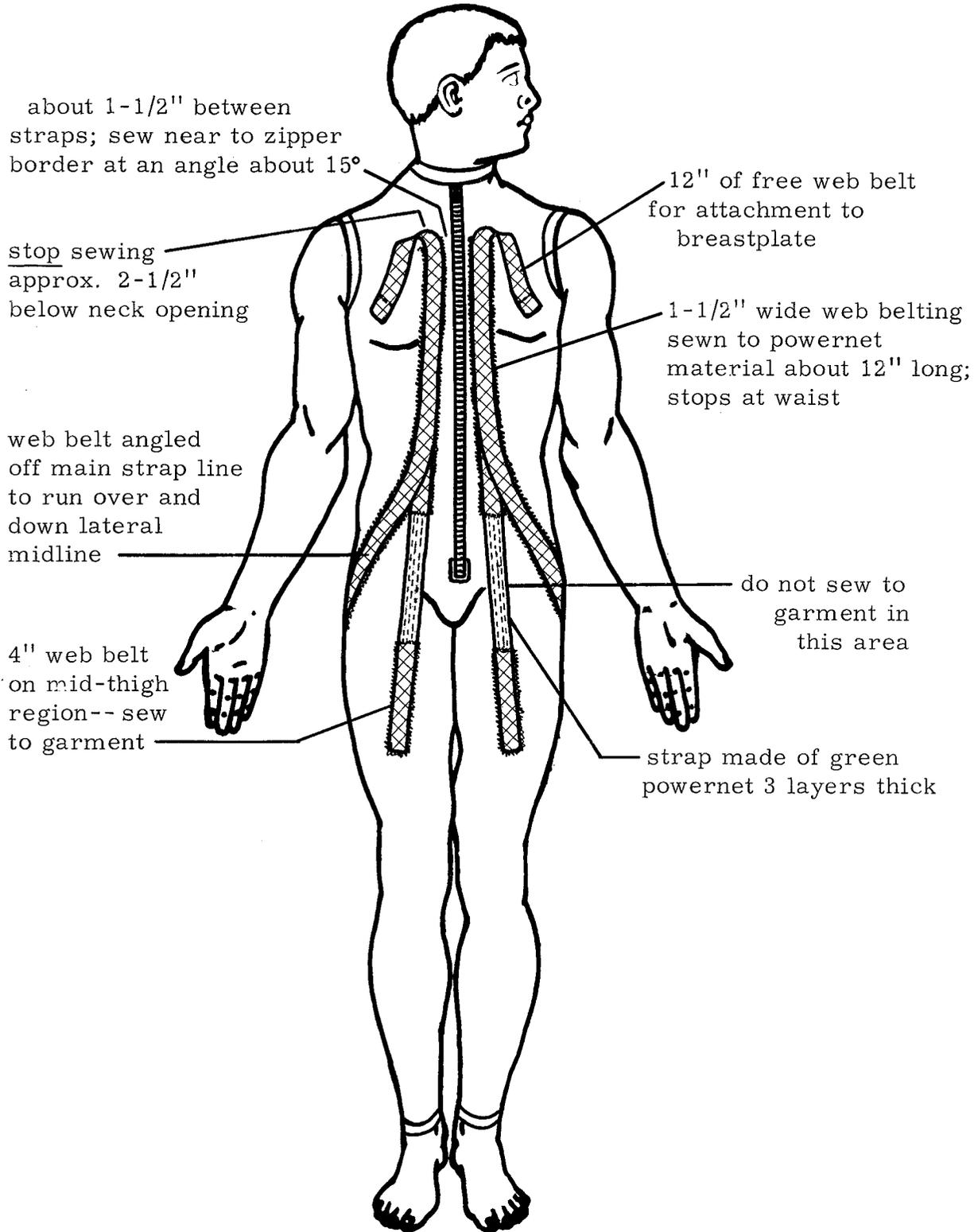rface of the hand proper will be included with each glove for the insertion of rounding devices. Hand counterpressure contributed by the gauntlets on PL#2 and #5 must be taken into account in the glove design. All gloves will end just above the wrist in an anti-roll band located to mate well with the garment sleeve ends.

Two sets of foot covers will be supplied with each garment. Insofar as engineering can be performed, the covers are to supply 75 mm Hg counter-pressure each. Counterpressure supplied to the foot by the half foot covers in layers #2 and #5 must be taken into account. Some material shall be removed on the anterior surface at the ankle joint line and the fabric resewn so that the footcovers assume a near right angle configuration in the neutral midline to facilitate donning. The zippers should extend to near the base of the toes. Encased open cell foam pads will be sewn into the post-malleolar depression areas on all covers. The footlets will end at the top in an anti-roll band which is located to mate with the appropriate suit layers. Care will be taken not to overpressurize the footcover-garment junction area.

SAS #8 and SAS #9

Using tailoring techniques employed in garments #4 through #7, fabricate two additional assemblies which shall be known as SAS #8 and SAS #9. A slip layer foundation garment will not be required since earlier ones are available. The number of power layers has been reduced to 4 total, and these shall be fabricated to possess the area counterpressures listed in the table below. Layer #2 will include special hold-down straps of 1-1/2" web belting, sewn in the configuration shown on the two following pages.

SAS #8 & #9--Layer #2
Helmet hold-down strap placement -- front view

about 1-1/2" between
straps; sew near to zipper
border at an angle about 15°

stop sewing
approx. 2-1/2"
below neck opening

web belt angled
off main strap line
to run over and
down lateral
midline

4" web belt
on mid-thigh
region-- sew
to garment

12" of free web belt
for attachment to
breastplate

1-1/2" wide web belting
sewn to powernet
material about 12" long;
stops at waist

do not sew to
garment in
this area

strap made of green
powernet 3 layers thick

SAS #8 & #9, Layer #2
Placement of helmet hold-down straps--rear view

not shown--breastplate

1-1/2" between straps

1-1/2" (1-1/4") web belt sewn to power-net torso, about 8" long

12" free web belt

end stitching of belt 2-1/2" below neck

junction--web belt & powernet strap

powernet strap made of green material folded into strap (3 layers thick) and sewn to suit layer

mid-line seam
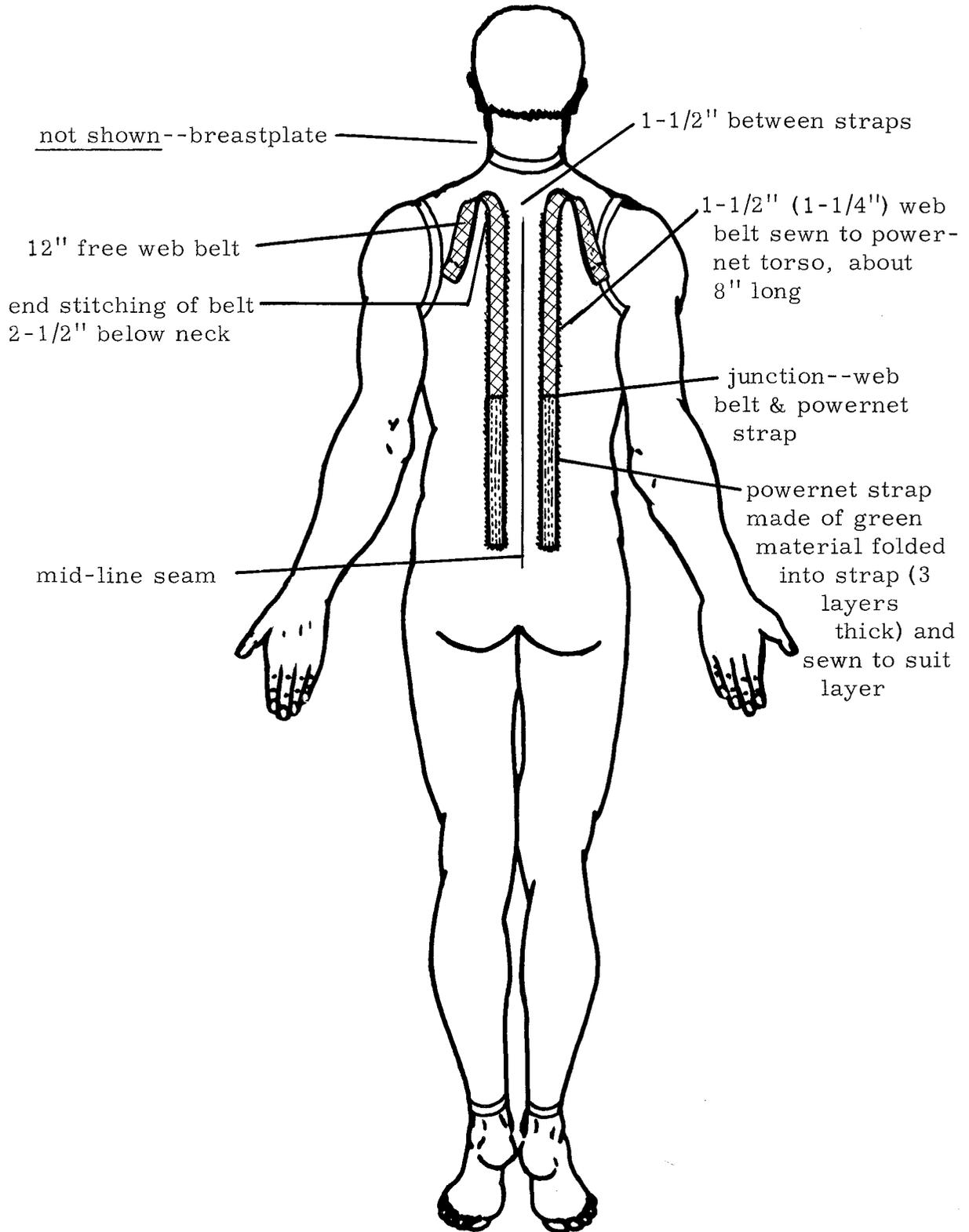
	torso	upper arm	lower arm	upper leg	lower leg
#1-Bobbinet layer	15	40	38	40	38
#2-Powernet layer	35	40(80)	38(76)	40(80)	38(76)
#3-Bobbinet layer	15	40(120)	38(114)	40(120)	38(114)
#4-Powernet layer (torso only)	35	40(160)	38(152)	40(160)	38(152)

SAS #10 (Second Phase)

The following are the assembly layers, in donning order:

Slip layer. -- unaltered from earlier assembly; select on basis of individual tailoring. (Note: the torso pressurizing breathing bladder assembly is donned immediately over the slip layer.

Helmet-bladder restraint garment. -- Its purpose is to limit bladder expansion and assist in preventing helmet rise. (See drawings labeled "helmet bladder restraint garment, front and rear views.") The torso section will be custom fitted to subjects and be constructed of a suitable non-stretch fabric, e. g Nomex. The top will be securely anchored to the split ring baseplate by clamping the material between the breastplate and the baseplate. The vertical length will be determined by fitting to be the minimum allowable for donning. A full length front midline zipper (#8 or larger), a rear midline zipper opening at the top (8" long, #2), and 2 lateral midline zippers (about 8" long, #2) opening at the scye line will allow entry. Circumferential size adjustments will be made by placing two each mid-lateral anterior lace take-ups (about 10" long). Approximately 1" of adjustment should be allowed per lacing. Eyelets should be positioned at approximately 1" intervals and be large enough to pass a heavy shoe string or equivalent. The fabric should limit the bladder to a maximum expansion of 1" upon pressurization up to 200 mm Hg. The non-stretch fabric will join below the umbilical line (double seam) to a leg-lower torso segment taken from an earlier garment. The bobbinet legs shall supply at least 25 mm Hg counterpressure over the maximum thigh dimension. Extra elastic material (powernet) will be included in an arch of material in the rear

to allow for subject torso bending. The torso shall end at the scye (no sleeve) and will be finished with a bias tape cover. All seams should be extra heavy or double to prevent pulling or ripping under tension.

Second helmet-bladder restraint garment.--Its purpose is to assist the primary helmet-bladder restraint garment. (See drawings.) This layer shall be a full-body garment with a torso section of non-stretch (Nomex) material and limb segments of bobbinet. The limb segments from earlier garments may be used; however, they should supply a minimum of 25 mm Hg over the largest circumference, e. g. thigh. Junction of the elastic leg section and the non-stretch torso section should be along the anterior leg-torso crease and below the buttocks in the rear. A strap of non-stretch material approximately 1" wide shall pass through the crotch for joining the elastic leg segments. The sleeves should be sewn along the original junction line. The vertical length of the torso fabric shall be minimum allowable for donning. This length will be determined initially from subject measurements and finally during fitting trials. The neck opening will be sized to fit snugly (when closed) into the angle formed by the junction of the baseplate and breastplate assembly--hence covering the shoulder portion at the breastplate. A full length torso zipper (size #8) will be inserted along the front midline of the torso section.

Arm balance layer. -- This layer will be modified from an earlier full body bobbinet layer and will be used to balance the pressurization of the arms with that on the legs (1st restraint garment has no sleeves). The leg portions of the selected garments will be removed just below the iliac crest line; however, fabric will be left to pass through the crotch to serve as an anchor for the garment. The sleeves will be unaltered, except counter-pressures should be checked and adjusted so that a minimum of 30 mm Hg is supplied over the largest arm circumference. The torso pressurization should remain at the original 15 mm Hg total.

Full body bobbinet layers. -- Two each full body bobbinet garments will be selected from earlier assemblies based on individual tailoring. These garments will be unaltered except for counterpressure adjustments. These garments should supply 15 mm Hg each on the torso and a minimum of 30 mm Hg and 25 mm Hg on the largest circumference of the arms and legs respectively.

Optional full body bobbinet layer.-- A third full body bobbinet layer will be used if found necessary to enable subjects to breathe at pressures in excess of 170 mm Hg. This garment will also be selected from earlier assemblies and the pressurization adjusted to develop the best possible full body assembly pressure balance.

Girdles. -- Two girdles each of the heavy powernet fabric will be fabricated to augment pressurization of the upper thigh-lower torso (below bladder) and to improve the pressure transition across the area of the body. One girdle will simply be made by removing the proper section from an earlier powernet garment. The girdle will extend from just above the knee to the top of the iliac crest. A single zipper (#4) will extend along the front midline from the crotch to open at the top edge. Counterpressure will be adjusted to supply up to 35 mm Hg over the thigh area. The counterpressure over the torso area will be reduced in gradient fashion so that at the top edge only counterpressure sufficient to hold the girdle in position will be retained, i. e. about 15 mm Hg. Cut edges will be bordered suitably to prevent raveling.

A second girdle will be constructed of powernet fabric which possesses an adjustable counterpressure feature. The torso tape layer from two SAS#2 garments will be modified to girdle form.

Four of the three inch wide tapes with Velcro closures will cover the thigh and three tapes will cover the hip area. The tapes should be positioned such that closure is along the lateral midline. The two pieces will be joined along a line running from front to back through the crotch so that tapes from both encompass the hip area and tapes of each individual section will pressurize the thighs. The girdle will be tailored in position on a subject and adjusted to produce a maximum of 45 mm Hg counterpressure over the thighs (tapes fully closed).

Gloves, pads. -- Gloves and molded rounding pads will be selected per each individual subject from existing supplies.

Footcovers.-- Footcovers (booties) will be selected from earlier assemblies.

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Front View

anchor fabric (Nomex)
and reflect down underside
of breastplate; adjust ver-
tical length to minimum
for donning

end torso at scye
(cover with bias
tape)

take-up laces--
adjust for required
bladder expansion
(10" long)

lateral midline
zipper (8")

bladder (outline)

Powernet
fabric

bobbinet fabric legs
from earlier garment

split baseplate (locked)

breastplate (bottom edge
outline)

bladder (outline)

front mid-line zipper
(full length)

non-stretch fabric
(Nomex) torso section

rear midline entry zipper--
8 in.

non-stretch fabric--
Nomex

add--2" arch over
spine--powernet
fabric

bladder outline

lateral midline
entry zipper

powernet
fabric

bobbinet fabric

tailor neck opening to fit
into junction of baseplate
and breastplate when closed

sew sleeve to Nomex torso
section--double seam along
original

non-stretch fabric
(Nomex) torso section
--tailor to allow no
more bladder expan-
sion than #1 restraint
layer; fix length to
furnish maximum
restraint on breast-
plate

Bobbinet sleeve --
use earlier garment

full length front
midline zipper

take-up tuck on
fabric--tailor on
subject

Bobbinet leg section -
use earlier garment

sew leg to torso
along leg bend line

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APPENDIX B

Safety Protocol and Test Plan
For the Hypobaric Testing of the Space Activity Suit (SAS)

Purpose. -- The purpose of the proposed tests is to demonstrate the efficacy of a custom fitted elastic leotard garment called the SAS to satisfactorily protect a human subject for a 2-hour period at near vacuum conditions.

Test objectives. -- The primary objective is to expose at least one active human subject for a 2-hour period to a mean pressure of 20 ± 5 mm Hg absolute in a hypobaric chamber without the development of physiological problems. Success will constitute evidence that an SAS type garment could serve as the basis of a protective garment for astronauts during EVA.

Test facility. -- The hypobaric facility selected for use in these tests is the altitude chamber in the Department of Preventive Medicine, Aerospace Medical Research Laboratories, Ohio State Medical School, Ohio State University, Columbus, Ohio. The chamber type facility is man-rated and regularly used for human test work; it is equipped with an airlock, and has internal dimensions of 15' long x 7' diameter. The main chamber measures 8' x 6', is supplied with ample windows for direct observation of subject, and can be operated together or independent of the airlock. The maximum altitude attainable is 100,000 ft with a time to maximum altitude of 25 minutes. It is estimated that 15-20 minutes would be required to reach test altitude of 80,000 ft, if test system gas inputs are limited. The chamber is equipped with an intercom system and 3 separate oxygen breathing (demand) systems (2 automatic, 1 manual backup). The facility will be operated by trained and qualified personnel who will work directly under the supervision of a physician of international aerospace medical repute. The chamber is located at the Ohio State University medical center, one of the largest and best equipped medical facilities in the country. Test subjects are covered by a unique medical insurance policy, the details of which can be supplied upon request.

Test Plan. --

a. Number of tests: only one full test is required, which meets the test objectives (80,000 ft) outlined in the paragraph on "test objectives" above. However, some preliminary shakedown-training runs will be performed. Two or possibly three subjects will be used. The one naive subject will be given indoctrination training to 38,000 ft. The tests planned may be outlined as follows:

Test 1. Indoctrination to altitude; naive subject to 38,000 ft.
Test 2. Rescue drill; all personnel; subjects to 35,000 ft.

Test 3. Systems checkout with suited subject to 40,000 ft, 30 minutes.
Test 4. Test 3 repeated with second subject.
Test 5. Short test to 80,000 ft or maximum attainable; not to exceed 30-minute exposure.
Test 6. Full 2-hour test at maximum altitude.*

> *Several trials may be needed to obtain a full objective test due to equipment failures, subject problems, etc., or at the discretion of the test director.

b. General test--step outline:

1. Subject denitrogenation:2-3 hrs on 100% O_2; equipment preparation.
2. Subject briefing and pre-suiting measurements; subject on O_2.
3. Subject suited to 170 mm Hg counterpressure; subject on O2. (PPBS loop dumped to safe pressure on at least three occasions during donning to vent system N_2.)
4. Subject, in-chamber physician, and SAS system technicians enter chamber.
5. Systems check--"all OK" requirement.
6. Climb entire chamber to 35,000 ft.
7. Hold; subject status check.
8. Determine "go" status. (Run may be scrubbed by test director or subject for any reason.)
9. SAS subject enters main chamber; inner lock door closed; rescue physician and technician remain in the lock; lock pressure maintained at 35,000 ft level.
10. Climb main chamber, maintaining constant visual and audio contact with subject.
11. When maximum altitude obtained--time 0--test period begins.
12. Subject performs prescribed activities for 2 hours; physiological monitoring maintained; visual and audio control required throughout.
13. End of test; main chamber repressurized to equalize with lock at 35,000 ft.
14. In-chamber observer enters main chamber and assists subject in doffing SAS; helmet pressure reduced in coordination with garment removal and chamber repressurization.
15. Chamber repressurized; subject depressurized.
16. Debriefing; post test measurements and medical examination.

Note. The test is only to show how well the suit protects at altitude. No unusual stress--either environmental or physiological--is planned. The whole test will have been done many times at ground level with the same ΔP in the suit and helmet.

c. Measurements: In order to insure the medical well-being of the test subject, certain physiological variables will be monitored throughout the experiment. Additional pre- and post-test run medical tests will help determine changes which may have occurred during the run, e. g. fluid accumulation in limbs, hemoconcentration, sweat and water loss, etc. The measurements planned to be made during the run are the following:

1. Heart rate (HR) continuous analog recording.
2. Respiration rate: continuous analog recording.
3. Oxygen consumption ($\dot{V}_{O_2}$): event recording from the PPBS digital O_2 metering device (DOMD); continuous.
4. Blood pressure: analog recording at will (corrected for breathing pressure movement).
5. Mean skin temperature ($\bar{T}_S$): average of 6 skin disc thermistors; analog recording or individual temperature digital readout.
6. Rectal (T_{re}) and chamber ambient (T_a) temperature: digital thermometer; 10-minute logging schedule.
7. Breathing loop pN_2; analog recording or meter readout.*

*System pCO_2 buildup levels will have been determined during tests at 1 atmosphere.

An effort has been made to limit AC and high current usage in the chamber. A single umbilical is anticipated to minimize subject encumbrance.

Safety and Rescue. --

a. Safety maxims:
1. Loss of audio contact with the subject will constitute reason to terminate.
2. Qualified physicians will be stationed both in the lock at 35,000 ft and outside at ground level.
3. Visual contact with the subject will be maintained at all times.
4. The test director shall be a qualified physician other than the "in-lock" physician.
5. The subject shall not be allowed to dictate test conditions, except for repressurization. Otherwise the test controller will be responsible.
6. Qualified and trained technicians will be provided for chamber operators for observing the subject.
7. Practice and training of emergency rescue will be required.
8. Significant changes observed in "vital sign" measurements will be reported to the test controller immediately.
9. Oxygen system safety protocol will be enforced at all times.
10. Loss of signal for certain measurements may constitute reason to repressurize. This decision can be made only by the test controller.

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11. Subject bends or pressure equalization problems occurring during depressurization or repressurization of the slightest nature are to be reported. Chamber conditions hold until subject reports OK. Test controller decides strategy.

b. Hazards and rescue: The emergency rescue plan to be initiated in event of a test accident while the subject is at altitude is as follows:

1. Immediately main chamber and airlock are equalized at 35,000 ft; time required, approximately 6 seconds.
2. When inner lock door is free, physician enters main chamber to render first aid and assistance as needed. A trained SAS systems technician will be present with the physician as part of the rescue team stationed in the lock.
3. Meanwhile, the chamber is repressurized at a maximum rate consistent with safety.
4. Upon arrival at ground level, the subject is removed to the treatment room adjacent to the chamber.
5. Emergency equipment and supplies available on site will include drugs, O_2 respirator, defibrillator, etc. An independent medical consultant will be on hand to assist the rescue physician and test controller in deciding upon a course of treatment.
6. General medical treatment for burns, ruptured eardrum, trauma, shock, etc.: subject to be manually transported across street to emergency facility in the OSU medical college hospital. Personnel will be forewarned of the possibility of a hypobaric chamber emergency.
7. If hyperbaric treatment is required: a chamber at OSU may be available by the test date. If not, arrangements will be made to have a standby ambulance and airplane for transport of the subject to the nearest facility, Maumee Hospital, Toledo, Ohio. Personnel of this facility will be told of our test plans and forewarned by radio in the event of an emergency.

The emergency plan will automatically be in force in case any of the following events occur while at altitude:
1. Breathing system failure, especially explosive loss of pressure.
2. Fire. (CO_2 extinguishers will be located in the chamber.)
3. Unexplained syncope by subject.
4. By order of the test controller.
5. By request of the test subject, or rescue crew.

The test controller will be responsible and will determine whether an experiment will continue if bends or pressure-equalization problems develop. The general plan is to hold chamber conditions constant immediately upon report of either condition by a subject (or rescue team member) until a course of action is determined.

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