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FINAL REPORT ON DEVELOPMENT OF RESTRAINT MATERIAL AND TUCKED FABRIC JOINTS

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For

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1.0 INTRODUCTION

This document constitutes the final report of effort pursuant to the development of restraint material and tucked fabric joints for space suits. The effort was conducted for NASA/ Lyndon B. Johnson Space Center by ILC Industries under contract NAS 9-14244.

The objective of the effort was to evaluate and select a suitable restraint material for the exterior of space suits pressurized to 4.0 PSID for normal operations, and to develop and improve tucked fabric joints for motions associated with the human shoulder, elbow, knee, waist, hip, ankle, and wrist. The many attributes of the end items as detailed in the statement of work can be summarized to include structural integrity, simplicity, low maintenance, lightweight, high durability, low elongation, full range mobility, long life, and resistance to degradation in the operational environment.

The end items of this effort as defined in the statement of work included: definition of a suitable space suit restraint material and its fabrication techniques; prototype joints installed in an existing space suit; and a final report including technical data developed, materials investigated, and construction techniques. Additional end items dictated by support of manned cycle testing included the development and fabrication of a complete liner and vent duct system. The wrist joint development and fabrication was deleted as an end item. This effort was conducted by NASA-CSD as part of an in-house glove development program.

2.0 SUMMARY

A significant change in priorities occurred during the initial phase of the contract. The development of triaxial woven fabric and fabric coatings for restraint systems; and the development of unsupported and supported conformally molded bladder systems where dropped as prime objectives. The reasons are stated in the technical discussions following. Priority was shifted to optimization of the flat patterned tucked joint concept utilizing the best available biaxial woven Kevlar fabric, and off-the-shelf urethane coated nylon fabrics for the bladder. A further change in priorities or objectives was to demonstrate the feasibility of developing a one-size space suit without hip bearings, which would provide a high level of comfort and mobility for the 5th to 95th percentile male population.

Flat patterned joints were developed for the shoulder, elbow, waist, and knee. The brief area was redesigned to incorporate a gimbal ring at the hip. This provided the stability necessary to incorporate flat patterned hip joints without bearings, and improved the efficiency of the waist joint sufficient to incorporate 3 inches of vertical sizing in the torso. The arms and legs were fabricated to incorporate adequate length adjustment to accommodate the 5th to 95th percentile male population. The fabric used for fabrication of the restraint was a 5.25 oz/yd^2 blended Nomex/PRD-49 woven cloth. Tapes and webbings included a variety of constructions developed under NASA contract NAS 9-12995.

The bladder was fabricated from the same patterns developed for the restraint. All seams were joined, stitched and taped. The material was 5.5 oz/yd^2 urethane coated nylon. The tapes were 10 mil Perflex E (urethane) bonded with AF 770 (urethane) adhesive. The primary objective achieved was to demonstrate compatibility of a relatively non-elastomeric reinforced bladder with the flat patterned restraint concept.

A complete liner and vent duct system were also developed to complete refurbishment of the space suit. The liner was fabricated from 5 oz/yd^2 Nomex. The primary objective achieved with the liner was a significant improvement in ease of donning over previous suits. The vent duct system was intended to be a minimum effort to support DVT. The simplified system developed however is extremely light, flexible, kink restraint, and durable. Crush resistance is reduced, but could be increased if required.

Exclusive of hardware, the only components of the space suit not redesigned and fabricated in this program were the helmet, gloves, upper torso, and lower portion of the boots.

The program was considered highly successful in demonstrating the adequacy of the materials and design concepts in the economical manufacture of space suits of high mobility and durability. While some deficiencies in detail design have been noted in the end items, there have been none for which minor corrective fixes are not apparent.

3.0 TECHNICAL DISCUSSION

3.1 MATERIALS DEVELOPMENT

3.1.1 Restraint Fabric

Three areas for improvement of the restraint fabric used in the 8 psi suit programs were identified. They were; seam pull-out resistance, bias stability, and abrasion resistance. All were related to weave stability, or resistance to the yarns sliding over each other.

A new technique for weaving fabric had been under investigation by ILC to produce a single ply fabric equal in stability to bias plied fabric extensively used for balloon construction. This fabric produced exclusively by "Doweave", of Philadelphia is a triaxial construction consisting of two warp yarns laid at approximately 100 degrees to each other and interlocked with a fill yarn. It was theorized that a tight weave of this construction would be superior in bias stability, seam holding, and abrasion resistance. The emphasis for developing an improved restraint fabric was consequentially based on optimization of this construction.

Initial efforts to obtain a suitable restraint fabric of this construction resulted in a PRD 49 fabric of equal weight, tensile strength, and tear resistance to the biaxial woven fabric used in the 8 psi space suits. Due to a comparatively open weave, however, the fabric was inadequate in seam holding strength, abrasion, and snag resistance. If a higher count construction could be produced, which it could not with available equipment, the problem of non-availability of smaller denier PRD 49 yarn would have resulted in a very heavy stiff fabric. While both of these constraints may be temporary, there was no alternative but to drop this concept for the subject program.

An alternative approach was sponsored by NASA to produce a biaxially woven fabric similar to that previously used, but using pre-coated PRD-49 yarn. This approach was based on the excellent results with Beta fabric for the Apollo program. Problems in coating of the yarn and in weaving, however, prevented production of a sufficient quantity of this fabric for evaluation.

It was finally resolved to proceed with the program using the most recently developed and most durable biaxially woven PRD-49. The construction and physical properties of this fabric in comparison with the triax weave evaluated are given in Table 1.

3.1.2 Tapes and Webbings

The significant variety of Kevlar tapes, webbings and cords developed on the previous suit programs were deemed adequate for use in the current program without further development. The construction and physical properties of those used are given in Table 2. Specific applications are noted in the design discussions.

TABLE 1

RESTRAINT FABRICS

Description	Biaxial Woven PRD-49/Nomex	Triaxial Woven PRD-49
Weave	2/2 Twill	16th Variant Triax
Yarns/Inch		
Warp/Fill	113/71	32
Yarn Denier	200/134 (PRD-49) 200/100 (Nomex)	2/200/134 (PRD-49)
Weight (oz/yd^2)	5.25	5.70
Tensile (lb/in)		
Warp	880	700
Fill	800	650
Tear Strength (lb)		
Warp	66	70
Fill	58	50
Seam Strength (lb/in) 3/8 Single Felled, Top Stitched 1/8 + 1/8		
Warp	415	245
Fill	250	250

TABLE 2

CORDS AND TAPES

Type	Breaking Strength
1/16" Hollow Braid Cord	400
1/8" Hollow Braid Cord	900
1/2" Twill Tape	1200
1" Twill Tape	2400

3.1.3 Bladder Fabric

It was proposed to develop conformal bladder elements by thermal bonding or dip forming urethane over a reinforcing fabric. Samples were made by three distinct processes. One which had been effectively used to form selected interfaces on the 8 psid suit program was vacuum forming. The process is the same as that used to form rigid thermal plastic parts. A second method was to fabricate flat panels using heated press plattens to laminate urethane film to a reinforcing fabric. The third method was to dip coat urethane over preformed fabric restraint panels. Each of these techniques were tried with the objective of fabricating samples from which physical properties could be determined and the most effective materials and processes selected.

Numerous problems evolved from the beginning of this effort which eventually caused it to be set aside. Uniformity of film thickness and adhesion to the restraint fabric were immediate problems. Physical property tests showed that lightweight scrims or leno weave fabrics actually reduced the tear strength of the urethane film to values less than that of the primary bladder fabric used in the Apollo suits. Heavier reinforcements tended to produce laminates which were bulky, stiff, and heavy. Most significant, the experimentation necessary to optimize the concept to an acceptable level, and the lead times necessary to produce tooling for prototype suit components were projected to extend well beyond program termination.

Based on the above circumstances, and a reaccessment of the prime attributes of the bladder system in the then more definitized restraint design, it was decided to screen available urethane coated fabrics for fabrication of a bladder system patterned and joined to conform to the restraint. Of the several evaluated, a 5.55 oz/yd^2 laminate procured by NASA from Switlick Parachute Company was selected as having the best combination of properties.

The physical properties of this material and others evaluated are given in Table 3.

TABLE 3

BLADDER FABRICS

Type	Apollo MIL-C-19002	Switlik SPC-MS-73-1	Switlik SPC-MS-73-2	Ripstop (Unknown)
Weight	7.2	5.55	4.41	2.63
Tensile Strength	260/191	135/154	73/72	67/72
Ultimate Elongation	33/31	9.7/6.9	4.9/6.2	4.2/5.5
Tear	7.3/4.5	4.0/3.9	1.6/1.2	6.0/14.5

3.2 DESIGN APPROACH

While it was necessary to develop each suit joint as a complete functional component for evaluation, the function of each element of a prototype joint was apparent, and sufficient commonality existed between the various joints of the suit to establish general design criteria without a large number of trials. A natural result of this design approach was a high level of standardization in construction as opposed to optimizing each element of each joint to its specific function in the suit.

The knee joint was selected for initial investigation since it represented an unbalanced high range joint of adequate size to establish structural requirements for all but the waist joint. The elbow, shoulder, and ankle joints were subsequently developed based on the design criteria established for the knee.

The waist, brief, and hip assembly was developed as a unit because of a great degree of interaction experienced between the components. In order to conserve time and materials, this assembly was developed in half scale. Although some problems were encountered in scaling up to full size, they were not a direct result of the scaling operation, and considerable cost savings did result.

Throughout the development program prime consideration was given to keeping the design as simple as possible in fabrication. No special tooling was used, and all operations were preformed with basic sewer/cementer skills. While the development sequence did not always permit optimum sequencing of assembly of the prototype suit, this also was considered in the design.

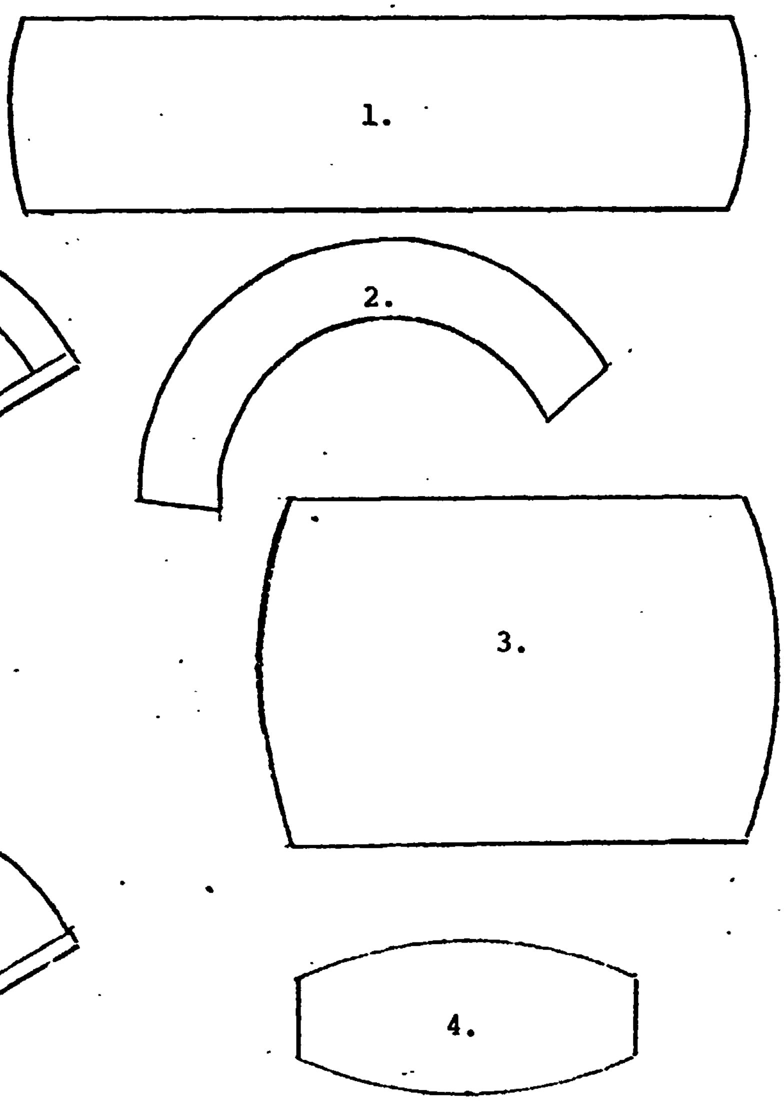
3.3 JOINT CONCEPTS

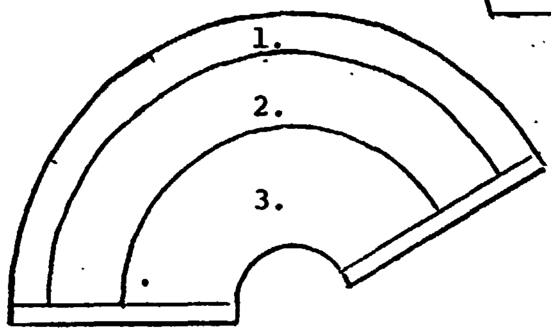
A prime objective of the program was to determine if the tucked fabric joints developed for the 8 psi suits could be produced more effectively using flat patterned construction and simplified seam techniques. Two alternate flat pattern concepts were evolved late in the 8 psi suit programs. One utilized four axial panels tc form the joint and the other utilized a series of transverse panels. These concepts are illustrated in Figure 1.

The former concept was used to fabricate the unsupported bladder components in the 8 psi suit joints and worked well because there were no transverse seams to impede bladder slip essential to its function. In a restraint however, two inherent design constraints were apparent. One, the material of construction must exhibit good bias stability adjacent to the axial restraint; and two, the patterning must be carefully controlled to minimize excessive distortion and resulting non-uniform hoop tension along the seams.

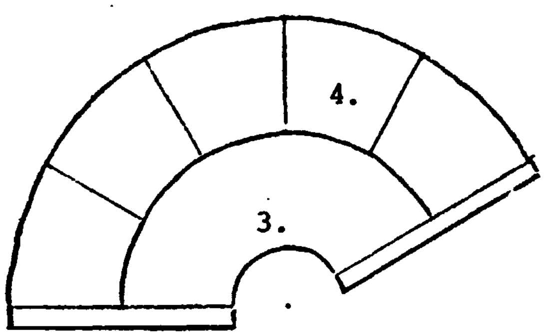
FIGURE 1

JOINT CONCEPTS





Axial Panels



Transverse Gores

The first cut at this concept involved modifications directed at minimizing these problems. The four panels were expanded to six to provide better conformity and the panels adjacent to the axial restraint were two layer bias plied to simulate the not yet available triaxial woven fabric.

This first joint showed evidence of non-uniform fabric loading, poor range, and excessive spring back. A second joint was fabricated using corrected patterns and triaxially woven fabric in place of the bias plied panels. With only minor improvement in performance, inadequacies in available triax weaves, critical patterning not conducive to sizing or adaptation to other joints, and difficult stitching requirements; the axial panel concept for joints was discarded.

The later concept using transverse panels or gores to achieve easement was more productive. Patterning for the first cut at this concept was developed from a geometric layout using 5 identical transverse gores to achieve a 150 degree bend. This joint functioned well, but was slightly unstable in favor of the bent mode and restricted in achieving the full theoretical range. Further analysis and experimentation with patterning resulted in a very effective second unit, and in the establishment of criteria for the design of all other joints.

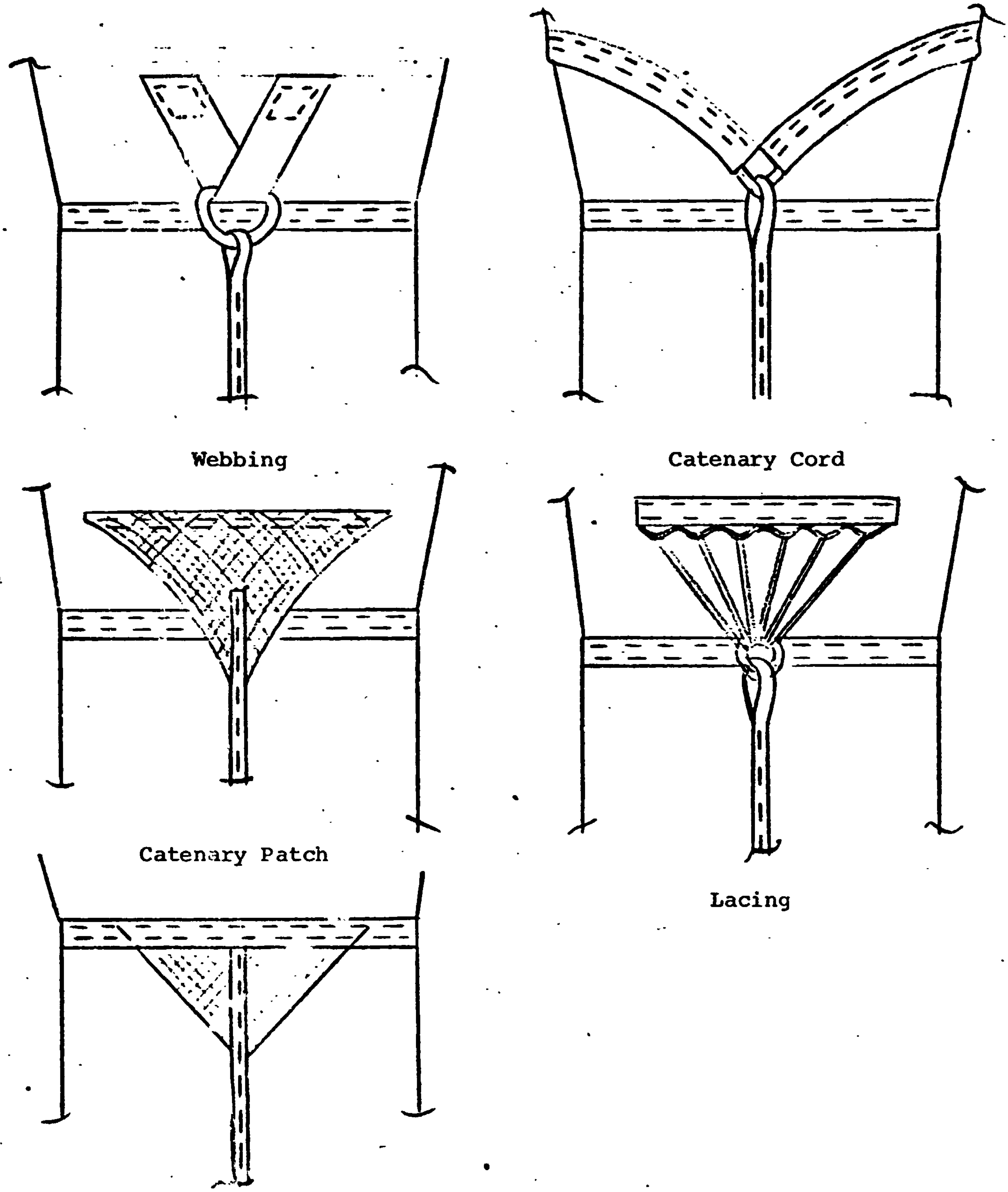
3.4 AXIAL RESTRAINT CONCEPTS

In the process of establishing the basic pattern approach for the joints, various axial restraint systems and terminations were investigated. It has been considered desirable to have an axial restraint system which was independent of the joint restraint proper to the extent that it could be changed out in the field on evidence of wear, and could be sized to be preloaded when pressurized to relieve the joint side seam of axial load. To this end, a knee joint was fabricated to incorporate a sheath in the side seam to hold an axial restraint cord. This system resulted in a bi-stable joint, and confirmed the need for the axial cord to be securely anchored to the restraint so that both transverse and axial displacement is totally eliminated.

Axial restraint terminations investigated are illustrated in Figure 2. Those systems which involved webbings or lacing proved ineffective due to the inherent higher elongation of these constructions relative to the base fabric, insufficient available transition area for implementation, and bulk and complexity of construction. The catenary cord system resulted in excess hoop tension in the cord with subsequent deformation of the joint and axial extension. The triangular based fabric load patch evolved from studies of webbing systems and woven catenary load patches. This system proved most effective in overall

FIGURE 2

AXIAL TERMINATION CONCEPTS



performance, simplicity, and ease of fabrication. Its implementation was further enhanced by the determination that the load distribution patch could be installed in the first element of a joint without significant effect in range and torque. This eliminated the need for any transition area between the joint and adjacent components.

3.5 SIZING

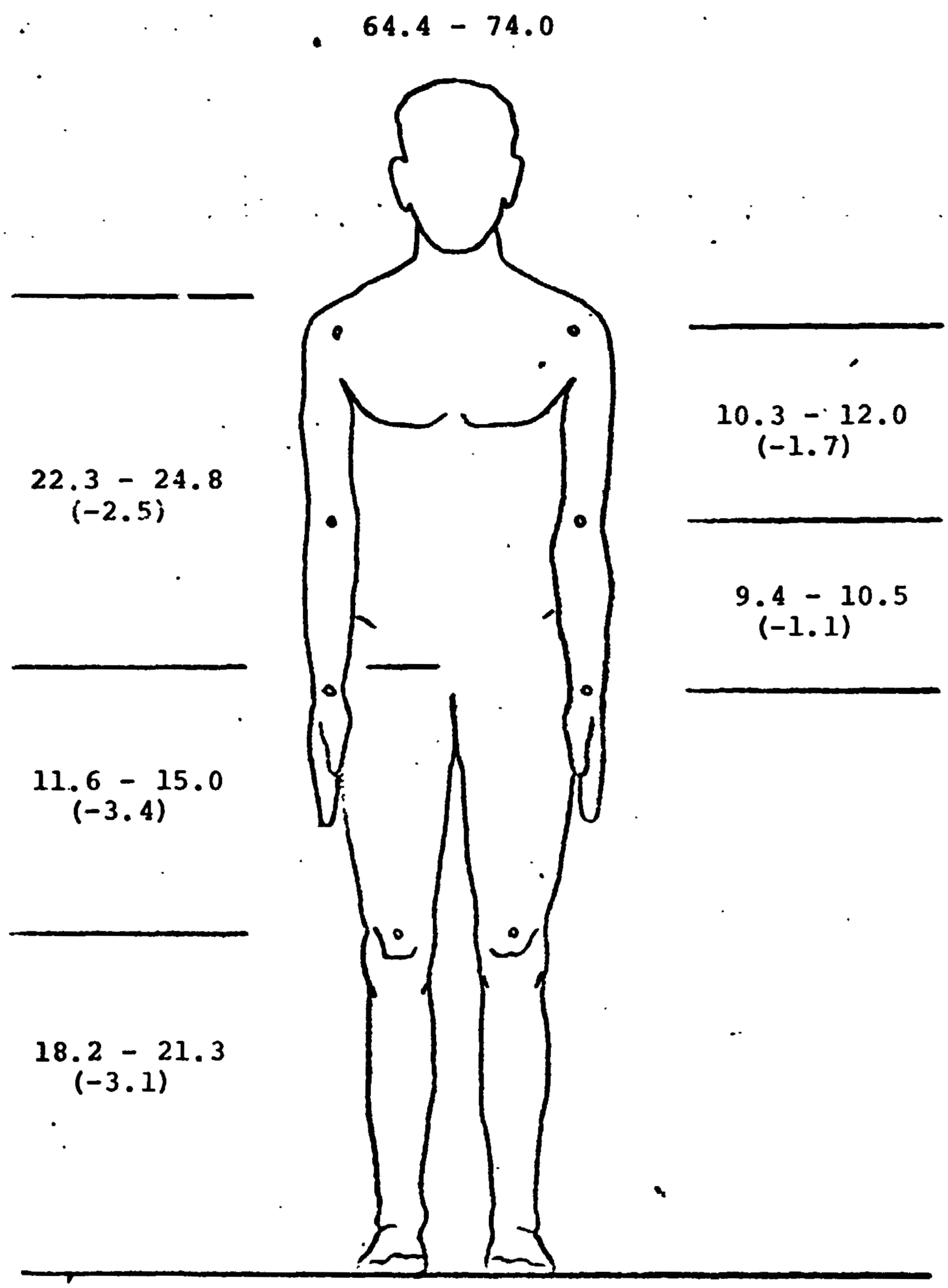
Before proceeding with detail joint and suit design it was necessary to perform a sizing study. The purpose of this study was to establish the length and location of sizing elements which would make it possible to adjust the suit from the 95th percentile male to the 5th percentile male and maintain joint centering. It also served to establish the maximum length available to the various joints.

Circumferential dimensions were basically established by the disconnects and bearings, and by prior designs which met easement requirements. One critical circumferential determination however was that of the gimbal hip ring. This was established at 15 1/2 inch I.D. by trial fit of a mock-up ring on a group of representative subjects.

The results of this study as it was applied to the development program is shown in Figure 3. In spite of this effort some discrepancies were apparent in sizing of the end item DVT suit. Based on fit checks with subjects ranging from 5 feet 8 inches to 6 feet 1 inch, the torso was one inch too short, and the legs

FIGURE 3

ANTHROPOMETRIC DATA
95% OF U.S. ADULT MALE POPULATION



two inches too long. The torso length was subsequently corrected, but the discrepancies in the legs remained with the result that the knee joints could not be properly centered for short subjects. Two other discrepancies related to sizing were apparent in manned mobility evaluations. The shoulder joint was too short resulting in restricted range, and the hip was incorrectly patterned resulting in a wider than desirable crotch.

3.6 DETAIL JOINT DESIGN

3.6.1 Knee Joint

The first cut at the knee joint was deliberately made to conform to a strict geometric layout even though it was known to not be most effective. This was done to establish a base line from which to access limitations and establish progressive design criteria. As such it was laid out to incorporate five identical front gores of 30 degrees, each gore had a ratio of 2:1, center vs. edge. The back panel was laid out to the same width as the cord of the front gores and was terminated at each end to include a 1/2 gore easement. This was done to incorporate a slight over center capability as opposed to a totally unbalanced joint.

Seam allowances were added to incorporate 3/8 inch single felled seams. The side seams were turned to the back and a one sixteenth inch hollow braid lacing cord was laid over the side seam and butted to the join seam as an axial restraint. No effort was made to design a specific termination for the restraint cord on this unit.

The joint demonstrated about a 30% loss in theoretical range at 4.0 PSID. Initial lock-out was apparent in the areas of the gores adjacent to the axial restraint cord. Further restriction was apparent in pre-extension of the joint at the ends and into the straight sections added to the joint for test. The joint was also slightly unstable in favor of the bend mode.

A second joint was fabricated to correct these deficiencies and add an axial restraint termination. The termination was for design evaluation only since the axial restraint in the leg is normally continuous through the knee. The pattern corrections involved changing the gores from theoretical curves to circular or constant radius curves, adding one more gore, and increasing the width of the back panel to equal the arc of the front gores. The circular gores, in addition to increasing easement adjacent to the axial restraints, are more easily developed for sizing and adaptation to other joints. The axial restraint termination consisted of a two ply triangular section (folded) sized to have its apex just off the first gore seam when butted to the end of the joint. This element is tacked to the edge of the joint before installing the restraint cord. The restraint cord is laid over the element, turned under just short of the location of the end join seam of the joint, and sewn through with heavy thread. The base of the triangular element is subsequently joined into the end seam of the joint.

This joint exhibited excellent range, low torque, and good stability with no apparent evidence of improvement potential. The design and construction details described are illustrated in Figure 4. The performance characteristics with comparison to the OES tucked fabric knee joint are shown in Table 4.

3.6.2 Elbow Joint

The elbow joint was patterned in accordance with the guidelines established for the knee. Only five gores were incorporated however, plus what could be construed as a half gore in the wrist cone, and a half gore in the upper arm cone. The use of half gores not only add to the range of the basic joint but when properly oriented complement design of the cones. This brings us to a more general discussion of the use of biaxial fabrics in restraint design. Contrary to earlier precepts, the bias slip of biaxial fabrics can be used to advantage in space suit design, and only rarely present problems. In the subject suit this property was used to simplify the development of all conical sections, to simplify the hip patterning, and to improve the breaking characteristics

FIGURE 4

KNEE DESIGN

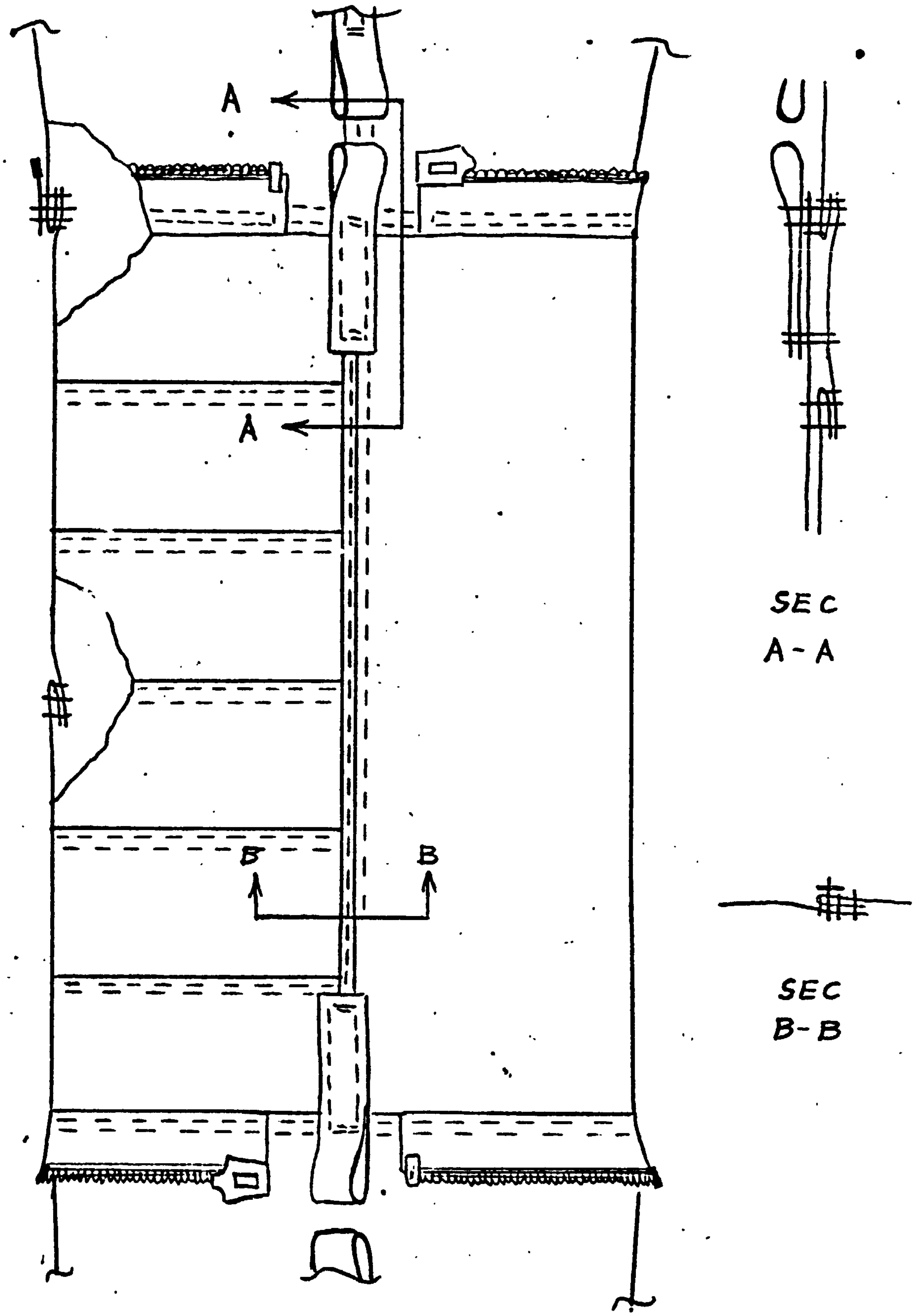


TABLE 4

TORQUE VS. BEND ANGLE

Flat Patterned Knee at 4.0 PSID

Angle (^{o})	0	10	20	30	40	50	60
Torque (in.-lb.)	28.1	20.2	10.1	0	0	0	0
Angle	70	80	90	100	110	120	
Torque	0	0	0	7.3	14.6	22.5	

OES Knee at 4.0 PSID

Angle (^{o})	0	10	20	30	40	50	60
Torque (in.-lb.)	32.8	28.0	25.6	21.6	20.8	20.0	17.6
Angle	70	80	90	100	110	120	
Torque	12.8	0	31.2	57.6	88.8	113.6	

Flat Patterned Shoulder at 4.0 PSID

Angle (+^{o})	0	10	20	30	40	50	60	70
Torque (in.-lb.)	0	10.5	15.8	19.5	24.4	27.0	35.6	42.0
Angle (-^{o})	0	10	20	30	40	50	60	70
Torque (in.-lb.)	0	8.3	12.8	19.5	16.5	22.5	30.0	37.5

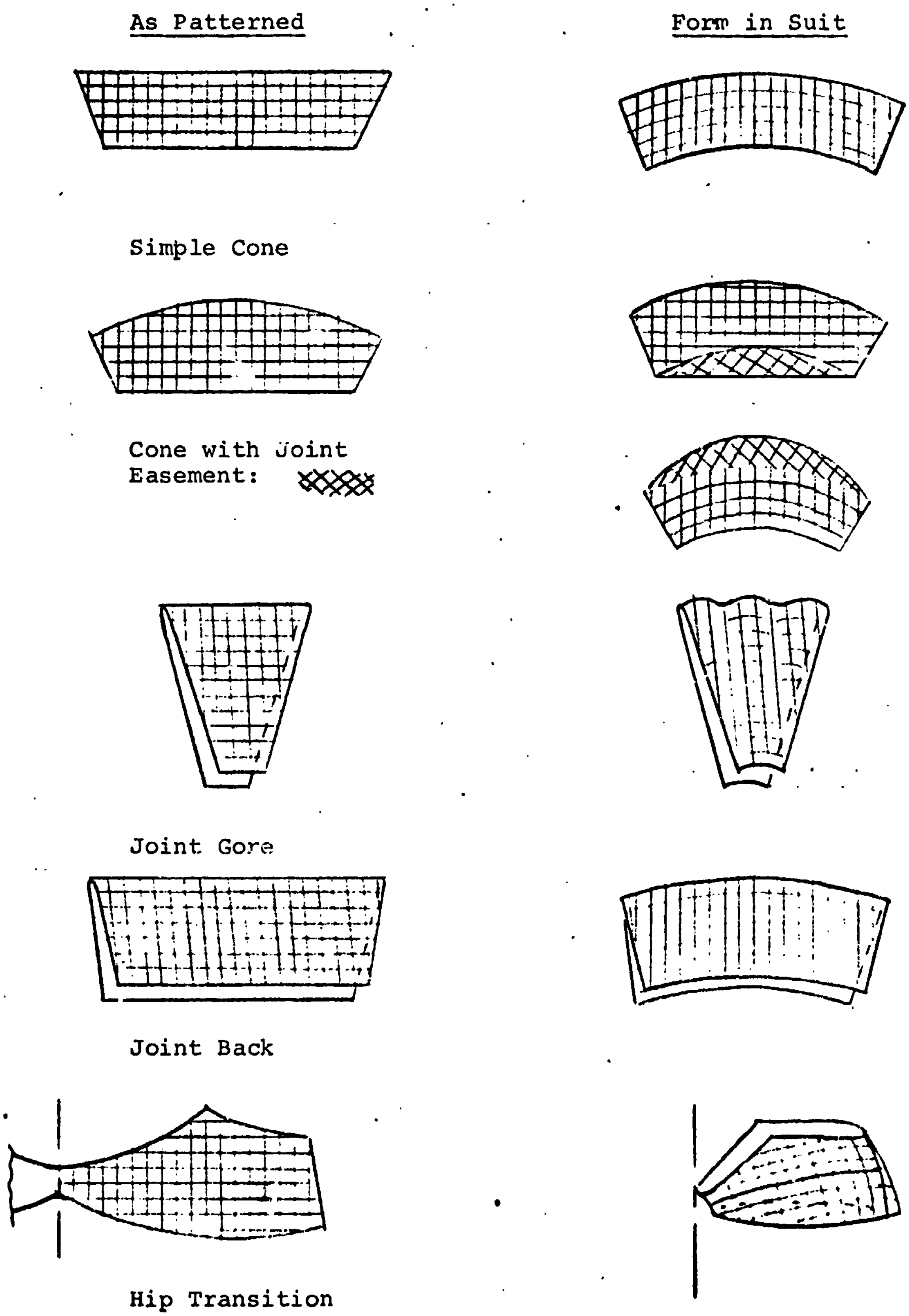
and conformity of the joints. Illustrations of this application are shown in Figure 5.

The elbow joint was fabricated with 2 inches sizing capability in the cone above the joint and 4 inches of sizing capability in the wrist cone. After fit check it was apparent that the sizing in the arm cone above the joint should be eliminated and the cone length reduced to a minimum required to achieve the circumferential change into the arm bearing. This would permit a slightly longer shoulder joint for improved mobility and still retain adequate elbow centering and overall length adjustment for a wide range of subjects.

The elbow joint was not tested for torque vs. range. Both were subjectively judged highly acceptable, cycle testing was not performed because the construction was the same as the knee which was tested and was subjected to approximately 25 percent lower loads.

FIGURE 5

BIAS APPLICATION



3.6.3 Shoulder Joint

The shoulder joint was a considerably greater challenge than knee or elbow because of its low length to diameter ratio and the severe diameter change from scye to arm bearing. A taper in the joint proper had been found undesirable because of a strong tendency to stack to the smaller end. This produced a spring back tendency to the neutral position. It was also determined undesirable to design an unbalanced joint as used in the OES because of a randon tendency for the joint to track into alignment contrary to the desired motion (not always evident in controlled mobility exercises). In short, development followed the guidelines established for the knee and elbow, but was not as successful due to the limitations noted. Three gores were incorporated in each side of the joint plus the half gore in each end cone. Because no sizing adjustment was required, the restraint terminations were located in the cones. In hindsight, a much more effective joint would have resulted by the simple addition of a fourth gore in each side. As was later evident, the added overall length could have been taken out of the upper arm.

This joint was tested for range vs. torque and was cycled 150,000 times in each direction. As can be seen in Table 4, the torques were higher than those of the knee and total range was less an desired. The cycling test did demonstrate an adequate structure. In theory and based on experience, a fourth gore would increase range by 30 percent and reduce torque by 50 percent through the nominal range. This should be fully acceptable.

3.6.4 Waist Joint

The waist joint in the OES was tapered and was not rigidly anchored at the bottom end of the axial restraints. This resulted in only about 50 percent efficiency and significant variation in torque and range with pressure. Elimination of the taper was no problem but rigidizing the brief to hold the waist axial restraint proved impossible with only fabric structures. Using half scale mock-ups, numerous pattern modifications, bias orientations, webbings, and triaxial fabric were tried. The brief persisted in distorting to a predictable shape which represented an equilibrium of hoop load and plug load vectors under pressure. The resultant load line from the crotch to the waist restraint termination always approximated 30 degrees to the vertical. This placed the waist termination too high to be effective. To correct this condition a gimbal ring was incorporated in the hip to rigidly support the crotch and the lower waist axial restraint. A stress analysis was performed to determine the minimum cross-sections in the gimbal ring which would provide a yield strength of 12 PSID. The final configuration incorporated consisted of two 6061-T6 aluminum concentric split rings 3/8 inches thick by 1 1/2 inches wide. The rings were bolted together with splits opposed to form a continuous ring of 15 1/2 inches I.D. x 3/8 thick x 1 1/2 wide. The ring was finished with a full radius on all edges, polished, and anodized.

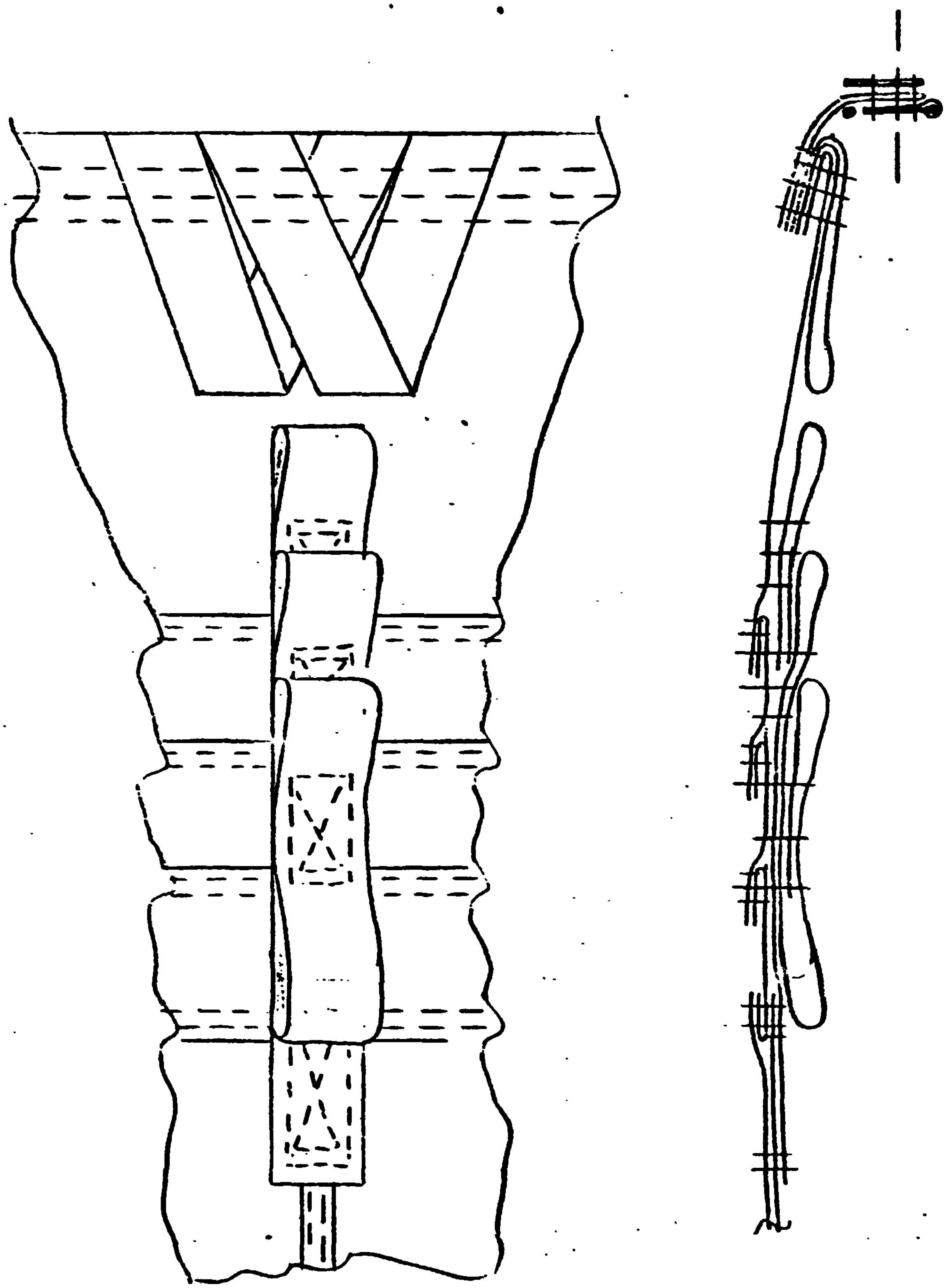
Following the guidelines previously established, a two gore waist joint of 14 1/2 inches diameter was developed with end cones to interface with the gimbal ring and the waist disconnect. The upper cone was truncated 15 degrees to match the disconnect angle and had 3 inches of vertical trunk sizing incorporated into the axial restraint terminations. Details of this construction are shown in Figure 6. The waist was later modified to incorporate three narrower gores and restraint zippers to improve control of the waist when taken up for smaller subjects.

3.6.5 Hip Joint

To achieve the transition from the brief to the thigh dictated a truncated conical hip joint. As previously noted, however, conical joints invariably stack to the small end. This would lock out the upper end of the joint where flexing was most desired. To preclude this, the joint elements were developed to form a toroidal section with all diameter reduction incorporated in the thigh cone. This produced a bloused effect or bulge in the upper thigh which was not particularly attractive but was functional.

FIGURE 6

WAIST AXIAL RESTRAINT



The first cut at this configuration incorporated only one element in the joint proper plus easement in the upper brief and thigh cone. When pressurized, most of the easement was lost in stacking of the thigh cone and poor mobility resulted. A second joint element was incorporated with both having greater easement in the back area. Mobility was greatly improved and the bulging was less apparent. This final configuration is still in need of minor modification to reduce the crotch width and shorten the thigh cone. In the process it is considered possible to gain even greater hip range.

3.6.6 Ankle Joint

The prime objective in redesign of the ankle joint was to lower the center of flexure for better tracking and demonstrate that the flat patterned concept in the joint would not detract from what was a highly mobile, low torque joint, in the OES and EIS suits. To this end the existing joint was removed from the EIS boots and the boots cut down one inch. The tucked joint was replaced with two gores, front and back with a reduction in joint length of 1 1/2 inches. The result was to lower the center of flexure 1 3/4 inches. The shorter joint lacked the apparent range of the original, but due to improved tracking, was demonstrated to not impede mobility.

In developing small joints such as the ankle and waist there is a legitimate question as to the advantages in design and fabrication of flat patterned joints vs. tucked joints. The materials and joining methods are more than adequate in either configuration, and in a small balanced joint the tucked concept is simplier in construction. The fact remains, however, that there is no way for an independent bladder to track or fully interface with a tucked joint, and no convenient way to seal a tucked joint with integral bladder. In this respect the flat patterned small joints are still a viable alternative.

3.7 AXIAL RESTRAINTS

It was the objective of this design effort that the restraint fabric and join seams see only constant and and predictable hoop loads in the suit. All axial loads, both from pressurization and manned loading are carried by cords and webbings joined to form a continuous load bearing structure with the hardware.

One sixteenth inch hollow braid cord pressed flat and stitched over the side seams with one row of heavy (hood) Kevlar thread was used for the knee, elbow, and shoulder joints. In the elbow and shoulder the cords terminated in a one inch overlap on the triangular load distribution patches. In the knee the cords overlapped the 1/2 inch axial restraint webbings in the leg cones.

Except where altered in rework, the axial restraint in the waist consisted of double thickness one inch webbing terminating in two inch loop around the hip gimbal ring at the bottom, and a series of 3/4 inch sizing loops at the top. The top loops were interfaced through a 3/8 inch diameter pin to a load distribution construction of one inch webbing at the waist disconnect. See Figure 6.

One eighth inch hollow braid cord was used in the ankle joint and hip joint. The cord in the ankle joint was the original EIS boot restraint cord, and was terminated in a tie-off loop bridging the boot restraint closure (zipper) to a mating loop in the lower leg cone restraint. In the hip the restraint cords were terminated by overlapping the adjoining restraint tapes. A one inch webbing was crossed over the inboard hip restraint cords in the crotch and was terminated in double thickness 2 inch loops over the hip gimbal ring.

The axial restraint system as designed is considered adequate. Several failures which occurred in manned cycling were the result of deviation to the design requirements in rework.

3.8 BLADDER DESIGN

One of the advantages of the flat patterned construction techniques is the ability to incorporate a bladder which is fully conformal to the restraint. The advantages of this are the elimination of slipping and stretching of the bladder in flexing the joints. This in turn minimizes bladder abrasion and permits a non elastomeric or fabric reinforced bladder to be used. The intimacy of the bladder and restraint permit the same patterns to be used for both with minor correction for differences in termination at hardware interfaces.

Heat sealing of the join seams was investigated but was not pursued for the following reasons: Butt seaming was the only method deemed feasible without an exorbitant expenditure in tooling to conform to the many complex curves involved. Even butt seaming would involve considerable expense. While butt seaming was effective and reliable with the unsupported urethane film used in the OES and EIS suits, the same techniques are not as effective in urethane coated fabrics because of a lack of comparable physical properties in the urethane and the non uniformity of preloading of the sealing die by introduction of the fabric in intersecting seams. Finally, the use of stitched and taped seams was known to be reliable and was adequate to demonstrate the prime objective of compatibility to the restraint.

The construction technique used was to join the bladder components by stitching with a butt, or join seam, such that all raw edges were outside and the coated side of the fabric is inside. The seams were then overtaped with 1/2 inch wide strips of no mil urethane film centered over the join seam on the inside. The only problem which was encountered was a tendency for the tape to bridge the join seam when it was not pulled flat. This puts stress on the seamline tapes when pressurized and can cause tape separation or tear. It is recommended that the bladder seams in future efforts be top stitched 1/8 inch from the join seam prior to taping to insure that all seams lay flat.

Neoprene coated nylon bladder tape was joined to the exterior of the bladder on selected seams to bond to similarly placed tapes on the restraint. These are in turn bonded together with neoprene adhesive to form a secure but separable attachment of the bladder to the restraint. Attachment was made at the bottom of the waist joint, through the crotch, at the top and bottom of each knee, and at the top of each ankle joint. These were in addition to common attachment at all disconnects and bearings.

3.9 LINER DESIGN

To improve ease of donning the liner was patterned to conform to the bladder and restraint and secured to the bladder as deemed necessary to cause it to lay close to the bladder and not bunch up. To prevent snagging all seams were turned to the outside.

Attachment to the bladder was achieved by stitching velcro hook to the liner and cementing velcro pile to the bladder. Snaps were incorporated in all velcro strips to facilitate alignment.

The shoulder liner was made separate with the vent duct inside to permit free rotation of the shoulder element. The liner material was the same 5 oz. Nomex used in the OES and EIS suits.

3.10 VENT DUCT DESIGN

It was necessary to refurbish the vent ducts in the DVT suit for manned cycling. It was not desirable to expend the effort required to fabricate the ducts as originally designed, therefore, an alternate inexpensive method was sought. The method selected involved interweaving 1/2 inch wide strips of bladder fabric through the coils of the spring-like stainless steel core used in the original design. A cover, also of bladder cloth, was then bonded around the coils and to the strips. This produced a very durable and flexible duct. The duct would not kink or close on flexing but did not have much resistance to crushing.

4.0 GENERAL CONSTRUCTION

4.1 MARKING AND CUTTING

It is important that the restraint patterns be laid out in exact alignment to the warp or fill of the fabric. They were marked with soft pencil, then coated to approximately 1/8 inch to either side of the marking with AF770 adhesive. The adhesive makes cutting easier and prevents raveling. The bladder and liner are laid out in the same general direction but are not as critical and are not coated.

4.2 STITCHING

Except for the joining of restraint cords and webbings, all restraint stiching was done with 200 denier Kevlar thread, 10 to 12 stitches per inch. The cords and webbings were stitched with 400 denier Kevlar thread, 10 to 12 stitches per inch. The bladder and liner were stitched with Size B Nylon thread, 10 to 12 stitches per inch.

Virtually all seams in the garment were joined 3/8 inches and top stitched 1/8 and 1/4 inches from the join seam. Exceptions were the upper torso side seams and seams adjacent to the waist disconnect. These seams were 1/2 inch with a third top stitch for added strength. All restraint seams were coated on the inside with AF770 adhesive to resist pull out and fraying. In addition, all tape loops were coated on the inside to resist abrasion.

4.3 BONDING

Only two adhesives and one primer were used in the program. AF770 urethane adhesive, manufactured by Staley, was most extensively used. Its use included coating of restraint fabric on cutting lines, edge-locking and bonding of stitched restraint seams, bonding of bladder seam tapes, end coating of webbings and cords to prevent fraying, and coating of high abrasion areas of restraint loops. It was also used with a primer for bonding of the bladder to machined aluminum hardware interfaces. The only constraint on its use was to neoprene coatings to which it does not adhere and in bonds which must be separated for maintenance. Typical application involved one full coat on each surface to be joined. This was allowed to dry a minimum of 30 minutes. This was followed by a second tack coat on each surface. The adhesive goes through a very aggressive but short (5 to 10 minute) tack phase in cure. This limits the length and complexity of areas which may be bonded in one operation. The adhesive can be "re-tackified" with Mek for rework, but is not recommended as a standard procedure. The adhesive is used as received without cutting. The material has a shelf life of one year or more in a full container tightly sealed. When activated with 1.0 percent accelerator by weight, it gels within one to four hours, depending on temperature and exposure.

Neoprene adhesive, N-136, manufactured by Staley, was used to bond the restraint and bladder together. This adhesive has a much longe_ tack period, and the joints are readily separated with toluene without affecting the AF770 adhesive bonds. Both facilitate bladder installation and removal. Its special application is conventional for neoprene adhesives and well documented.

The primer used for joining the bladder to aluminum surfaces was PR-420 manufactured by Products Research and Chemical Corporation (PRC). It is a two-part system, mixed in accordance with manufacturer supplied directions. A thin uniform coating is applied to the aluminum and allowed to dry a minimum of 16 hours before bonding.

4.4 ASSEMBLY

4.4.1 Restraint

The torso restraint was fabricated in three sub-assemblies including the front torso, rear torso, and the hip and thigh cone assembly. The front and rear torso assemblies were joined at the side seam, then joined to the waist disconnect flange tape with a double thick (folded) 1-1/8 inch wide strip of restraint fabric cut on a bias. To insure accurate fit to the waist disconnect flange, the flange tape was fabricated by marking a disc of 2 ply, 18 ounce neoprene coated and laminated nylon fabric to match the disconnect flange. The center was cut out only after joining the 5/8 inch beaded nylon loop tape and the bias fabric joining strip.

In fabricating the hip and thigh cone assembly, the side seams were joined last before joining to the torso. The knee and lower leg cone, boots and ankle joint, lower arms and shoulder joints were each fabricated as separate assemblies. The axial restraint systems were installed during fabrication of the sub-assemblies with the exception of the out board axial restraint on the hip and thigh cone assembly. These should be installed as a final step to permit them to overlap the waist and knee restraints independent of the join seams. Failure to do this after rework resulted in failures during manned cycle testing. One inch wide strips of neoprene coated fabric, cut on a bias, were secured to the restraint in designated seams via the top stitching. The strips were cut short and not joined in the side seams to reduce bulk and ease installation of the bladder.

4.4.2 Bladder Assembly

The bladder was assembled in the same general manner as the restraint except top stitches were not used. The use of one row of top stitches 1/8 inch from the join stitch is recommended, however, to facilitate taping. One-half inch wide 10 mil unsupported urethane (Perfex E) sealing tapes were bonded to all seams. Neoprene coated nylon bias strips one inch wide were stitched into the join seams prior to taping to interface with the similar strips on the restraint. Snap loop patches, fabricated from bladder fabric, were bonded to the interior of the bladder to secure the vent system. These were located adjacent to the out board side seams at the top of the elbow, in the upper and lower leg cones, and in the transition panel just above the hip joint. One-half inch wide strips of nylon velcro pile were bonded to the bladder with AF770 adhesive to interface with velcro hook on the liner. A cut-away butt seam was incorporated in the center of the lower leg cone for removal of the boots.

4.4.3 Liner

Again, the sequence of assembly of the liner was the same as the restraint and bladder. One half inch wide nylon velcro hook was stitched to the liner to interface with the velcro pile bonded to the bladder. Snaps were incorporated in the velcro as required to insure alignment on installation.

5.0 CONCLUSIONS

It can be reasonably stated that all objectives of the Tucked Fabric Development program were met, while new fabrics were not developed for the restraint and bladder, readily available existing materials with proven resistance to natural aging and chemical attack, and good mechanical properties were demonstrated entirely suitable to space suit construction. Relative to simplicity and economy of construction, only 25 patterns were used to fabricate the restraint, bladder, and liner exclusive of the upper torso, gloves and boots. All seams were of the simplest butt joined, single felled type stitched on one type machine. No tucks, pleats, gathers, or special attention to take-up was required. The only hand stitching was in securing the restraint to the bearings.

The one million flex cycles to which a knee joint was subjected without functional failure clearly demonstrated the durability of the materials and construction methods. Those failures which did occur in manned cycling were not catastrophic in nature, and were a direct result of failure to follow established construction guidelines in rework.

Donning and comfort were significantly improved over all previous suit designs. Mobility, while not improved, and in some cases less than observed in the OES suit, was still adequate and greater than that available in the A7LB suit. Of more significance, except for mobility modes predetermined now essential to extravehicular activity, the suit is considered capable with minor redesign of mobility equal to or greater than the OES suit.

The incorporation of the hip gimbal ring is considered the most significant advance in space suit design resulting from this program. With it waist joint efficiency was improved sufficient to permit torso length adjustment. Brief stability was achieved for improved comfort and fit and a functional soft hip joint was made feasible. With these improvements the gimbal ring remained totally inabstrusive to the subject in the suit.

The second most significant advance is the demonstration of compatibility of the flat patterned joint construction to identically patterned, reinforced, bladder construction. Except for this characteristic, the flat patterned construction is not clearly superior to pleated constructions. Both concepts exhibit good torque, range, and stability characteristics. Their prime difference exclusive of bladder interface lies in fabrication of the multiple seams of the flat patterning vs the hand pleating and tacking of the other. The multiple seams are more compatible to volume production economy and control than hand pleating.

Additional advances may be cited in the elimination of taper in the joints and further insight into the effective use of biaxial fabric in complex pressurized systems.

The added complexity and potential loss in reliability of the torso restraint system by addition of the sizing system must be subjected to further study in arriving at the final design configuration. The design presented in the DVT prototype is not the only option, and any change in waist disconnect location would require a re-evaluation of torso sizing. Its retention is also dependent on whether it ultimately becomes the only constraint to a one sized suit.

While the effort clearly demonstrated that a suit could be designed to adjust to a wide range of subjects, it also pointed out some limitations which must be overcome before it is fully practical. The areas of take-up in sizing tend to produce an uncontrolled bunching and diving of the restraint. This can limit mobility and cause pressure points on the subject. The areas of the suit where sizing is required are also the areas where conical elements are required, the combination is even more unstable. The more the take-up, the greater the problem. The discontinuity in the primary axial restraint lines created by sizing elements cause structural design problems which complicate fabrication. The techniques used were fairly effective but do not represent the only design options.

6.0 RECOMMENDATIONS

As in all programs of this nature, several areas of potential improvement were noted after completion and testing of the prototype. Most of these have been noted in the design section of this report but are here summarized for clarification.

Incorporation of sizing in the arm above the elbow resulted in a constraint of the shoulder joint to a length which did not permit full mobility. The shoulder joint should be lengthened and increased in range by the addition of a fourth gore. Elimination of the sizing above the elbow would maintain the maximum overall length of the arm with adequate elbow centering and sizing take-up retained.

Two cuts were required to achieve a reasonable degree of hip mobility. The final cut still left room for improvement. Joint easement is marginal, the crotch is too wide, and the thigh cones are too long. All of these areas can be significantly improved by a single recut, but even further effort may be desirable to insure optimum fit and mobility.

The incorporation of the hip gimbal ring led directly to consideration of integration of it and the waist disconnect. A preliminary study has shown many potential improvements with such a configuration. The waist disconnect is properly sized and structurally adequate to double as a hip gimbal ring. By removing the circular bearing and disconnect from the upper waist area, the upper torso can be made elliptical thus significantly reducing the fore and aft envelope dimensions of the total EMU with back pack and control unit. By locating the bearing below the waist joint the crewman can bend in the direction to which he turns his body, a more natural movement which was partially achieved in the OES suit through the hip bearings. The greatest problem in donning, that of engaging the disconnect is minimized by virtue of the disconnect being more accessible to the crewman and more flexible in positioning.