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TECHNICAL REPORT
NATICK/TR-77-8

**MANUFACTURING METHODS REPORT OF THE
DOUBLE WALL AIR INFLATED MUST SHELTER
MADE FROM THREE DIMENSIONAL FABRIC**



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Aero-Mechanical Engineering Laboratory

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This program was undertaken to develop three-dimensional weaving techniques which would produce integrally woven arch sections for inflatable double-wall structures of the type used by the military. Using present existing methods, these double-wall structures are constructed of coated fabric cut to patterns of the appropriate size and shape, and cemented or sewn together into the double wall unit. This method involves much hand labor, and the reliability of the numerous seams in the complete unit depends largely on the		

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20.ABSTRACT continued

quality of original workmanship.

By the integrally woven arch approach, most of the seams are eliminated and thereby reducing the unit's vulnerability to seam failure in the field. Using the three-dimensional weaving technique, the inner wall, outer wall, and connecting webs can all be woven together in one piece eliminating the present sewn and cemented seams. This new fabrication method, developed and evaluated under this program, specifically sought to achieve the following improvements:

- a. To develop three-dimensional weaving techniques, which could be used to manufacture integrally woven fabric, for the wall sections of double-wall inflatable shelters.
- b. To develop an economical method and equipment for spray-coating the exposed surfaces with synthetic rubber compounds equivalent to stand MUST shelter specifications.

Under this program, a three-section MUST shelter was fabricated of double-wall sections, each consisting of a single piece of fabric produced by a three-dimensional weaving technique. This report describes methods and equipment evaluated, recommends design, manufacturing procedures, and equipment required for production. It also includes projected costs for producing such shelters in quantity.

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PREFACE

This report summarizes work accomplished by the Aero-Mechanical Laboratory, (AMEL), Shelters Engineering Division under contract number DAAG17-73-C-0139 with the B. F. Goodrich Engineered Systems Co. Appended to this report is a report by Woven Structures (Division of Hitco), the principal subcontractor, who developed the special woven fabrics used in construction of prototype shelters.

This program was undertaken to develop three-dimensional weaving techniques which would produce integrally woven arch sections for inflatable double-wall structures of the type used by the Surgeon General in the MUST Hospital Complex. A three-unit MUST shelter was manufactured from fabric produced by a three-dimensional weaving technique. The program consisted of developing this technique as well as a method for spray-coating the exposed surfaces with synthetic rubber compounds equivalent to standard MUST shelter specifications.

This report describes methods and equipment evaluated under the program and recommends design, manufacturing procedures, and equipment required for production. It also includes projected costs for producing such shelters in quantity.

Mr. Donald B. Shaw of the Aero-Mechanical Engineering Laboratory served as Project Manager. Mr. Stanley J. Shurtleff of the Clothing, Equipment and Materials Engineering Laboratory assisted in the evaluation of material and coating techniques.

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MANUFACTURING METHODS REPORT OF THE
DOUBLE WALL AIR INFLATED MUST SHELTER

1.0 INTRODUCTION

1.1 Objective

This program was undertaken to develop three-dimensional weaving techniques which could produce integrally woven arch sections for inflatable double-wall structures of the type used by the military. Using present existing methods, these double-wall structures were constructed of coated fabric cut to the patterns of the appropriate size and shape, and cemented or sewn together into the double-wall unit. This method involves much hand labor, and the reliability of the numerous seams in the complete unit depends largely on the quality of original workmanship.

By the integrally woven arch approach, most of these seams are eliminated and thereby, reduce the unit's vulnerability to seam failure in the field. Using the three dimensional weaving technique, the inner wall, outer wall, and connecting webs can all be woven together in one piece eliminating the seams normally required to join them together under existing methods. This new fabrication method, developed and evaluated under this program, specifically sought to achieve the following improvements:

- 1.1.1 To develop three dimensional weaving techniques which could be used to manufacture integrally woven fabric for the wall sections of double-wall inflatable military structure.
- 1.1.2 To develop an economical method and equipment to apply a protective coating of synthetic rubber on the exposed wall surfaces.
- 1.1.3 Using these techniques, produce a three-section MUST (Medical Unit Self-Contained, Transportable) shelter which would conform, as closely as possible, to standard specifications for this type of structure.

1.2 History of the Program and Changes in the Contract

The original proposal for this program was submitted to the U.S. Army Natick Laboratories (USANLABS) on December 23, 1971, by Rubber Fabricators, Inc. (RFI), of Richwood, West Virginia. At the time, RFI was a division of HITCO, a unit of Armco Steel. Under the proposal, RFI would manage the program which also would involve other HITCO divisions, including Woven Structures, Inc. of Compton, California. Woven Structures, which has accumulated substantial experience in

three-dimensional weaving, was to produce the one-piece fabric for the MUST structure while RFI was to handle other aspects, including the coating and final fabrication.

- 1.2.1 On May 22, 1972, RFI was acquired by The B.F. Goodrich Company of Akron, Ohio, and became a subsidiary of the Aerospace and Defense Products Division. On April 3, 1973, USANLABS issued contract DAAG-17-73-C-0139 to RFI. Under this contract, RFI was to produce four units, each consisting of a one piece, integrally woven fabric reinforcement coated with Neoprene base coat and then with an outer coat of weather-resistant Hypalon. All sections were to conform dimensionally to the drawing requirements of the standard MUST shelter including floor, end panels, etc.

Upon receiving this contract, RFI subcontracted with Woven Structures, Inc. to produce, first, sample sections of the integrally woven double-wall panels for evaluation purposes, and then, when approved, to produce four full-sized wall panels themselves. RFI retained development of the coating procedure and fabrication of the detail parts required in the final assembly of the MUST structure.

- 1.2.1.1 On July 22, 1974, RFI was incorporated into The B.F. Goodrich Company through a statutory merger. It became the West Virginia Operations of B.F. Goodrich Engineered Systems Company, a new division which had been created in January, 1974, by merging Aerospace and Defense Products with Industrial Products Company, another B.F. Goodrich Division.
- 1.2.1.2 Woven Structures, Inc. meanwhile, encountered difficulties in weaving the one-piece wall panels. In the fall of 1974, responsibility for this contract was assigned to the New Products Department, of The Engineered Systems Company. A review of the program status and, in particular, the progress in the weaving of the arch section by Woven Structures, Inc. was made.
- 1.2.1.3 Woven Structures, Inc. were found to be making satisfactory progress in producing the required material and a 2-1/2 yard sample was submitted to the responsible personnel at the Natick Laboratories at a meeting held on October 29, 1974, for this evaluation. This sample was accepted as a successful demonstration of the woven arch construction.

Woven Structures, Inc. recommended that their contract be amended to call for three full size woven arch sections instead of four. They were required to vacate the building where the weaving loom was located by December 1st, which did not allow adequate time to complete the four sections required by contract.

- 1.2.1.4 As a result of this meeting, the contract with USANLABS was renegotiated, calling for a finished structure containing three, instead of four, double-wall sections. The contract with Woven Structures, Inc. also was modified to specify three, rather than four woven arch sections plus two shorter sections for evaluation.
- 1.2.1.5 The fabrication of the MUST shelter was moved from the Richwood Plant to the Grantsville, West Virginia Plant because it was more compatible with the Grantsville Plant's line of work.
- 1.2.1.6 A section of the woven arch measuring five yards long, was delivered to The B. F. Goodrich Company in Akron in November, 1974, which was used for the development of coating techniques. All three full-sized sections were delivered in late January, 1975.

1.3 Identification of Personnel

The design, fabrication and testing was assigned to Mr. J. T. Straga, as Project Engineer, under the direction of Mr. C. P. Krupp, Manager, New Products Development. Mr. Tony Petrosino supervised the fabrication and assembly at our plant in Grantsville, West Virginia.

Technical representatives of the U.S. Army Natick Laboratories assigned to this project by contracting officer were Messrs. D. Shaw, as Project Manager, and S. Shurtleff, in charge of the Material Evaluation.

2.0 DEVELOPMENT PROGRAM

The program to develop an Inflatable MUST shelter using the three dimensionally woven fabric for the structure consisted of a two-part effort:

- 2.1 Adapt the three-dimensional weaving techniques to the manufacturing of a structural fabric arch, dimensionally identical to the standard MUST shelter.

- 2.1.1 Develop a practical method of coating the three dimensional fabric with a synthetic rubber conforming to the requirements of that used on the standard MUST shelter and modify the detail design of the shelter to effectively use the woven arch material.

2.2 Development of One-Piece, Three Dimensionally Woven Fabric Arch

Woven Structures, Inc. was assigned the task of developing the three dimensional weave technique to produce a woven arch structure, dimensionally equivalent to the standard MUST section. This task consisted of developing the fabric construction, modifying an existing weaving loom to produce the 14 foot wide material to the proper radius, and to produce three sections of acceptable quality so that this three-section MUST shelter could be coated and evaluated by the U.S. Army Natick Laboratories.

An appendix attached to this report gives a complete description of the work accomplished by Woven Structures, Inc. detailing the problems encountered, their solution and their recommendations for producing this type of material in production quantities.

2.3 Development of Techniques and Equipment for Coating the Woven Arch Sections

a. Materials

Government specification MIL-C-43285B and the L. P. /P. Des. 42-70 set forth basic requirements for the coating materials. These requirements are discussed in the separate "Evaluation Report", which is a requirement of this contract, and therefore, will not be discussed in detail in this "Manufacturing Report".

A newly developed Neoprene Latex compound as base material and a Hypalon top coat material was the coating material which met the requirements of this specification. In the course of development of the coating, we found that the viscosity of Neoprene Latex as it is normally furnished needed to be modified for improved spray ability. This was done without affecting the physical properties of the dried film.

2.4

Application of Coating to Fabric by Hand Rollers and Brush

To test this application method, sections were cut from the five-yard long sample woven fabric panel provided by Woven Structures, Inc.

A piece of the fabric was attached to the two edges of a plywood panel with an air inflated polyethylene pillow behind the fabric to tension it in a manner similar to that expected to be encountered in coating a full size arch section. The following conditions were maintained in coating the various samples:

- 2.4.1 The pillow was inflated with air pressure to 0.5 psi.
- 2.4.1.1 A smooth, (wrinkle-free) polyethylene sheet separated the fabric sample and inflated pillow.
- 2.4.1.2 The fabric surface was tensioned in both directions.
- 2.4.1.3 The sample was held in a vertical position during application of the coating.
- 2.4.2 Eight successive coats of Neoprene latex were then applied at intervals of approximately one hour in order to completely fill in the fabric weave and produce a smooth surface. (The Neoprene latex requires 45 minutes to one hour to dry.) The samples were then coated with a ground coat of white Hypalon followed by two coats of olive drab and pale green Hypalon on adjacent areas of each sample. Test specimens were cut from samples made in this manner and tested to the physical requirements of specification MIL-C-43285B.
- 2.4.3 The Neoprene latex, when applied by hand roller or brush, tended to develop air bubbles, which remained on the surface for some time after each coat. As the water from the coating dried, the bubbles burst leaving pinholes on the surface. These areas had to be brush coated several times to produce a pinhole free surface. The result was an uneven coating of the latex with brush marks which could not be removed. This method of hand application could be used for coating the structure, but it was considered uneconomical and a more cost-efficient method of coating was sought.

2.5 Spray System for Coating Application

The high viscosity (20 to 25 seconds in a No. 4 Zahn cup) of the Neoprene latex compound (BFG Code No. 190X 63112A) made the search for a feasible spray system an extensive undertaking. The compound contains 50 percent fillers and curing agent and coagulates easily in spraying equipment.

Three major types of spray equipment were examined and tested as part of this investigation: standard air-atomized spray equipment with pressure container, airless spray equipment, and airless spray using a pressure accumulator with a bladder as the pressure source for spraying.

2.5.1 Standard Air Atomized Spray Equipment

Several standard paint spray guns of the air-atomized type were investigated.

- 2.5.1.1 DeVilbiss spray gun, type MBC, Model "L", was evaluated using 80 psi air pressure in the gun and 0 to 30 psi air pressure in the fluid container. Although the equipment did spray the material, its delivery rate was low and the pressure was not adequate to properly atomize the viscous latex which resulted in a very rough sprayed surface.
- 2.5.1.2 A DeVilbiss spray gun EGA, Model 502 was tried with several nozzle combinations. It too, produced an unsatisfactory surface due to poor atomization.
- 2.5.1.3 A Binks #18 spray gun, equipped with #66 fluid nozzle and #66 SD air cap, produced results similar to that obtained with the DeVilbiss gun.
- 2.5.1.4 All of these standard air-atomized spray guns were not designed for high air pressure to adequately atomize the high viscosity latex. Tests were made with the latex diluted with distilled water in amounts of 25 percent, 50 percent, and 100 percent of the original latex volume, in an attempt to improve the flow of the material. Although this reduced the viscosity, it also lengthened the drying time between coats. The poor surface obtained with air atomized spray equipment and its low delivery rate caused us to abandon this approach as a means of applying the Neoprene latex. This type of equipment was found to be

satisfactory for applying the Hypalon top coating which was solvent based.

2.5.2 Airless Spray Equipment

Two basic types of airless spray equipment were investigated: (1) air operated piston pump equipment and (2) electric motor driven diaphragm pump equipment.

Airless spray equipment is particularly suited for spraying high viscosity materials of all types at high rates of delivery with little or no overspray. We thought that this type of equipment could be used in spraying the Neoprene latex without dilution and produce a satisfactory surface.

2.5.2.1 Air Operated Piston Pump Airless Spray Equipment

A "Nordson" Model 64A single piston high pressure pump was evaluated using "Nordson" Model L and Model C-73 spray guns. The evaluation involved tips with 0.014", 0.009", and 0.006" wide orifices. The pump piston to air supply ratio of this unit was 15 to 1. With the factory air line pressure of 80 psi, we obtained 1200 psi fluid pressure at the gun tip.

The equipment worked reasonably well but delivered an uneven sprayed surface, full of minute air bubbles. Different size tips did not produce a significant improvement in the appearance of the sprayed surface. The use of smaller tip orifices did not improve the spray quality. The smaller orifices reduced the amount of latex delivered to the surface. This equipment did not provide sufficient pressure to adequately atomize the latex. Personnel of The B. F. Goodrich Adhesives Laboratory investigated the use of a similar single piston pump made by the Greco Company, but their results were no improvement over those obtained using the "Nordson" equipment.

2.5.2.2 Diaphragm Pump Airless Equipment

The equipment from two different manufacturers of high pressure diaphragm pumps was then evaluated.

2.5.2.2.1 The "Pulsa Feeder" Type CPD-3 pump made by Lapp Insulator Co. is a high-pressure hydraulic pump which at an operating pressure

of 3000 psi will deliver 1.75 gallons of fluid per hour. The maximum pressure rating is 3750 psi. The pump consists of two electric motors each driving a piston 0.25-inch in diameter which reciprocates against a hydraulic fluid contained in a reservoir which in turn pulsates a diaphragm which pumps the material to be sprayed.

This equipment demonstrated very low delivery rate when spraying the latex compound and was not considered further.

- 2.5.2.2.2 A Wagner Model ST-2700 pump produced by the Spray-Tech Co. of Minneapolis, Minnesota was used with a Graco high-pressure (5000 psi rating) airless gun in the next series of tests that gave encouraging results. This combination of pump and gun produced an excellent sprayed surface and delivered material at a high rate. Theoretically, it could deliver up to 1.25 gallons per minute at 3300 psi. Good latex atomization was obtained with fluid pressures of 2000 to 3000 psi. In these tests, a 150-square-foot area was sprayed in five minutes for an average of 30 square feet per minute coverage rate. Since we had trouble with the latex coagulating in the pump of the Nordson pump it was decided to run a prolonged test to determine if coagulation would occur with this equipment as well. To test the equipment, the pump was allowed to run for an extended period of time. After one hour, the rate of latex delivery decreased, and after two hours latex coagulated within the pump causing the pump to overheat. It required several hours to partially disassemble the pump and clean it. The pressure relief valve in the pump which contains a 1/32-inch-diameter orifice was completely plugged. To avoid this condition, the manufacturer suggested that we by-pass the pressure relief valve. A new part was sent from the factory with the relief valve removed, and the pump was retested. After one-half hour, the pump ceased to work. It was taken apart and 1/8-inch-thick disc of coagulated latex was found under the diaphragm.

We believe that a part of the accumulated latex under the diaphragm was formed during the first test and partly during the second test, and it was coagulated by heat generated by the rapid oscillation of the pump diaphragm. The latex build-up prevented fresh latex from being sucked into the pump.

The Wagner ST-2700 airless pump was not considered satisfactory for use in spraying Neoprene latex over a prolonged period of time because of the excessive maintenance which would be required. Although this type of equipment was not found to be satisfactory for applying the Neoprene latex, it would be ideal for applying Hypalon or other low

viscosity coatings because of its high delivery rate and minimum overspray. This equipment is compact and can be carried by one person. A hose up to 350 feet long can be attached to the pump and still provide adequate flow rate at the gun.

2.5.3

Airless Spraying using Pressure Accumulator with Bladder

Our investigation of commercially available pumps for airless spraying brought us to two conclusions:

- a. The Neoprene latex coating could be effectively sprayed using airless spray equipment if pressures above 1500 psi is used.
- b. Since commercially available high pressure pump equipment caused the latex to coagulate, special equipment would have to be custom-built for this purpose. Such equipment would have to be able to produce the high pressure required for complete atomization of the highly viscous compound and should not include moving parts or small openings that could become clogged with latex due to shear of the liquid.

To meet these requirements, we first proposed to use a pressure vessel filled with latex pressurized with nitrogen gas at the proper pressure for spraying. Under pressure, the latex would flow unobstructed, from the vessel, through the hose and into the spray gun. This setup, we expected, would minimize the possible latex coagulations. A study by our latex technical group showed that at very high pressures (3000 psi) the latex would absorb up to 2.50 times its own volume in nitrogen. This could cause the latex to foam as the pressure is released at the spray gun nozzle and sprayed onto the surface to be coated. Therefore, to work properly, this device would need some means of separating the nitrogen from the latex. We decided to evaluate a Greer-Hydraulics Corporation Standard Hydraulic Pressure Accumulator which contains a bladder which separates the hydraulic fluid from the pressurizing gas as a pressure source for spraying. Its design seemed suited to our requirements, and one of their standard five-gallon models was purchased for use as the pressure source for airless spraying.

B. F. Goodrich Drawing No. 5X2082 schematically illustrates the assembly of this modified pressure source. (See Figure 1). The pressure vessel was connected through a ball valve and fluid filter to

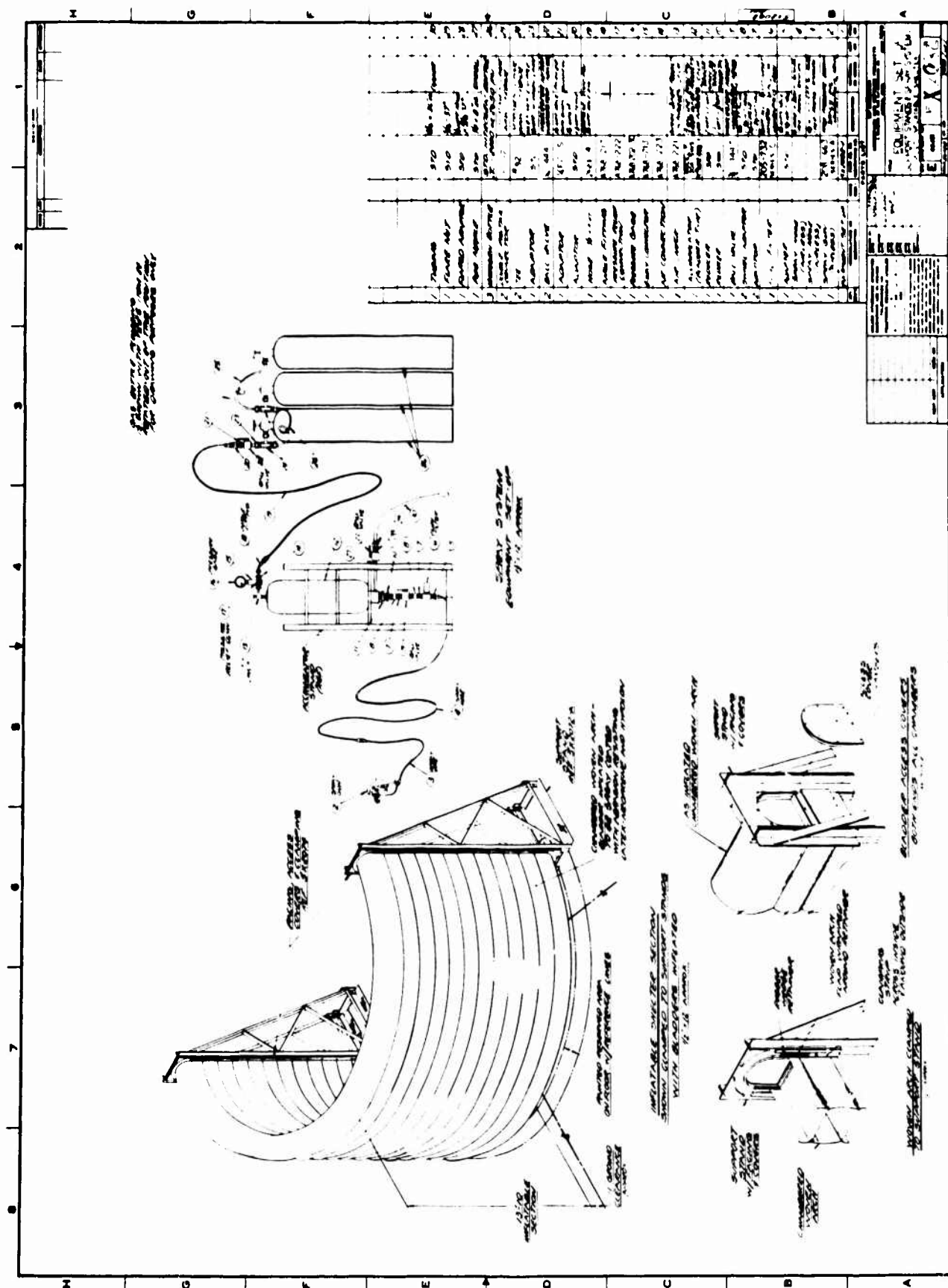
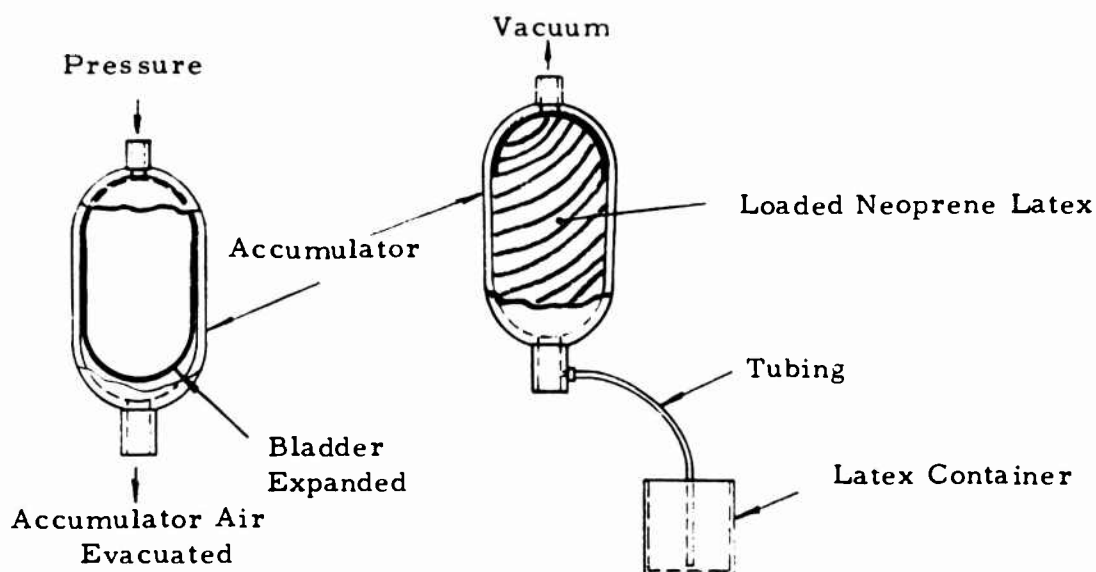


FIGURE 1: SPRAY SYSTEM AND SUPPORT STAND

50 feet of 1/4-inch-high pressure hose, which was connected to the spray gun. One or more bottles of nitrogen gas was used to provide the pressure required to force the latex from the opposite side of the bladder in the accumulator through the hose and out of the tip of the spray gun in an unrestricted flow. Since there were no moving parts to cause friction as the latex is delivered to the airless spray gun, we did not expect problems with latex coagulation.

Loading the latex into the pressure vessel through the small bottom opening that contained a check valve was found to be difficult. By adding a second ball valve and a three foot section of copper tubing, 5/16 inch in diameter, as shown in Figure No. 2, we were able to load the latex into the accumulator by first expanding the bladder with air pressure which forced all of the air from the accumulator. Once this was done, the copper tubing was inserted into the latex and the air in the diaphragm released. This action created a vacuum which sucked the latex into the accumulator below the diaphragm. When the diaphragm return to its unstretched condition, a vacuum was drawn on the diaphragm, which completed the filling of the accumulator with latex. See sketch below.



Neoprene Latex Loading Of Accumulator

Once the latex was loaded into the accumulator, pressure was applied to the top side of the diaphragm from one or more bottles of high-pressure nitrogen gas through a hose equipped with a check valve and pressure gage. The equipment was then ready for spraying. (Figure No. 3).

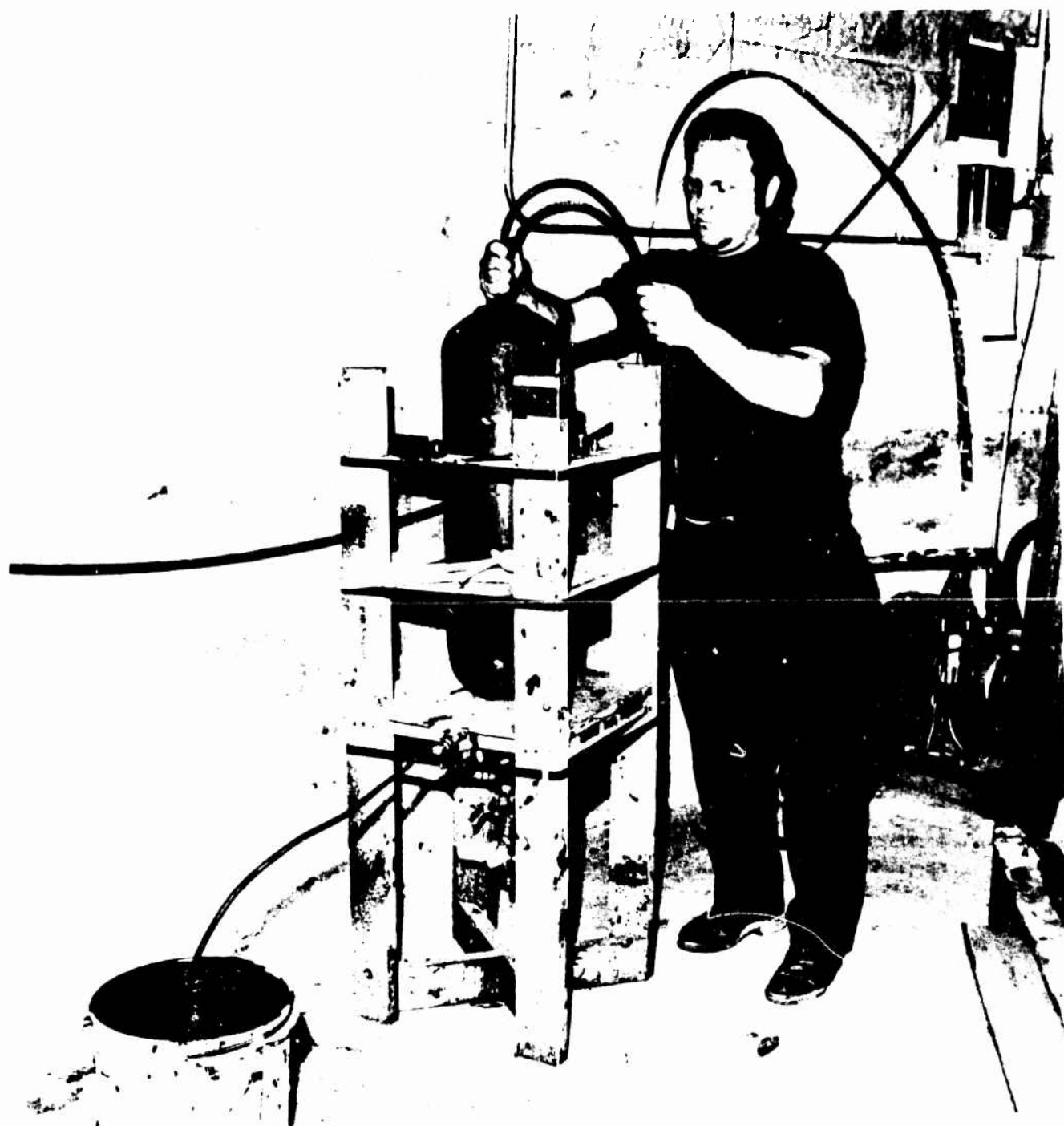


FIGURE 2: SUCTION OF NEOPRENE-LATEX INTO
THE BLADDER ACCUMULATOR

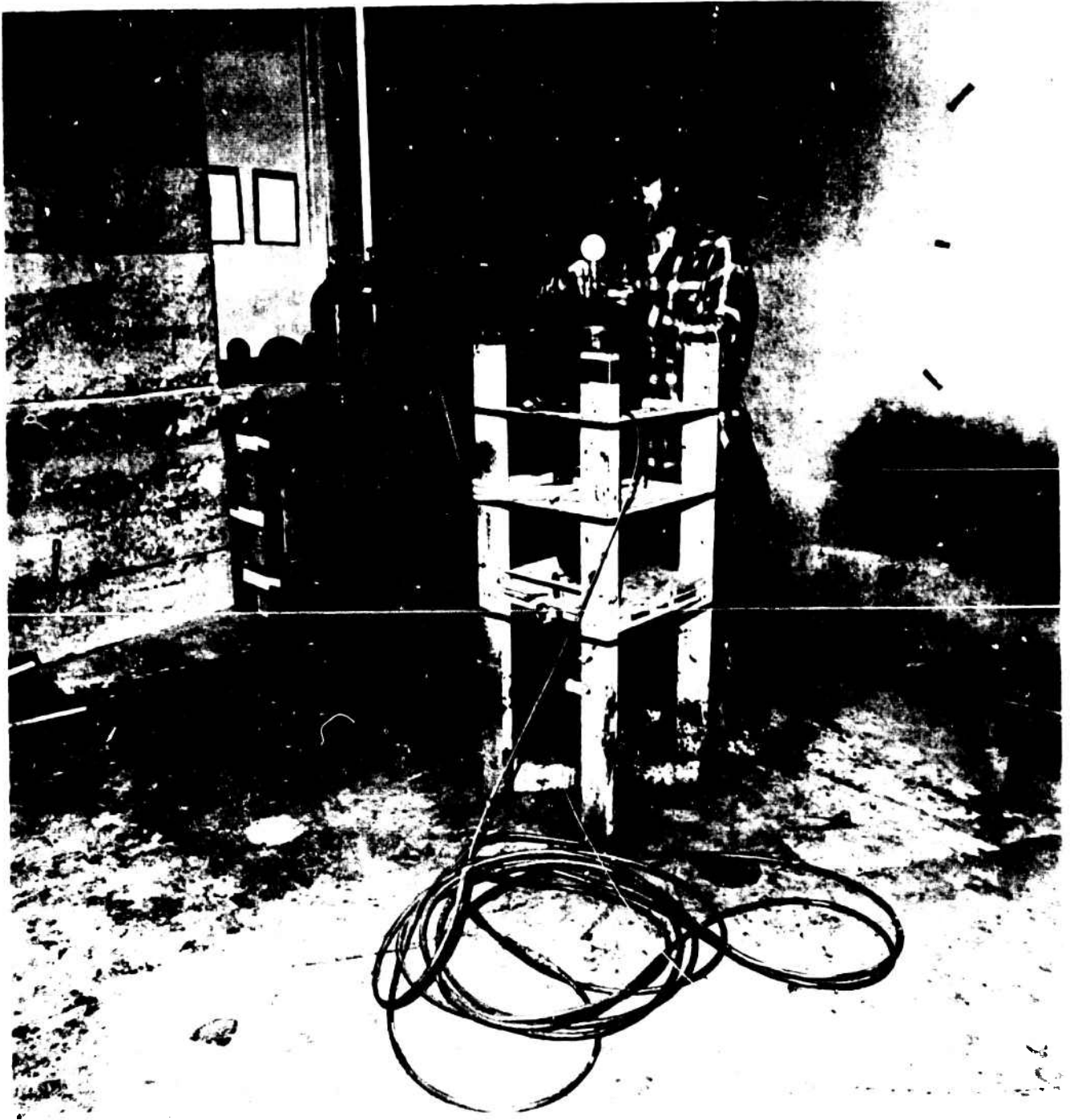


FIGURE 3: ASSEMBLY OF BLADDER ACCUMULATOR
SPRAY SYSTEM

To activate this unit, the pressure regulator valve on the nitrogen bottle was set to the desired pressure and the flow valve opened to pressurize the latex.

We found that the equipment worked best when a pressure above 2000 was used which reconfirmed the experience with the Wagner equipment, but a good spray pattern could be obtained at pressure as low as 1500 psi.

2.6 Laboratory Spray Coating Trials

2.6.1 Once the proper operation of the hydraulic accumulator pressure source for the latex was obtained, the equipment was then used to coat the sample arch panel provided by Woven Structures, Co. Although, this partial section originally measured 15 feet long, only 10 feet remained after fabric samples had been cut off for previous laboratory coating trials. The remaining section was 8 feet wide compared to 13 feet 2 inches for a full size panel. This section contained eight rather than twelve cells which hold the inflation bladders. The fabric section had the same radial arc curvature and cell opening dimensions as the full size arch sections. (Figure No. 4)

2.6.2 We investigated several bladder materials which would not adhere to the Neoprene latex coating when it was applied to the fabric walls by spraying. First, we tested extruded polyethylene tubing 0.004" thick. This tubing did not adhere to the latex material coating but developed pinholes that expanded to the point where it was not possible to maintain air pressure in the bladder without a constant flow of air which was undesirable.

We investigated several other grades of polyethylene tubing of different thicknesses and molecular weight. The low molecular weight, soft tubing expanded easily but developed pinholes. The harder high molecular weight tubing wrinkled then cracked in the wrinkled areas causing air leaks.

2.6.3 Since polyethylene tubing by itself proved unworkable, we decided to use bladders made of Neoprene coated fabric encased in a polyethylene tubular sleeve to keep the air retention bladders from coming in direct contact with the Neoprene latex during the coating of the wall surfaces.

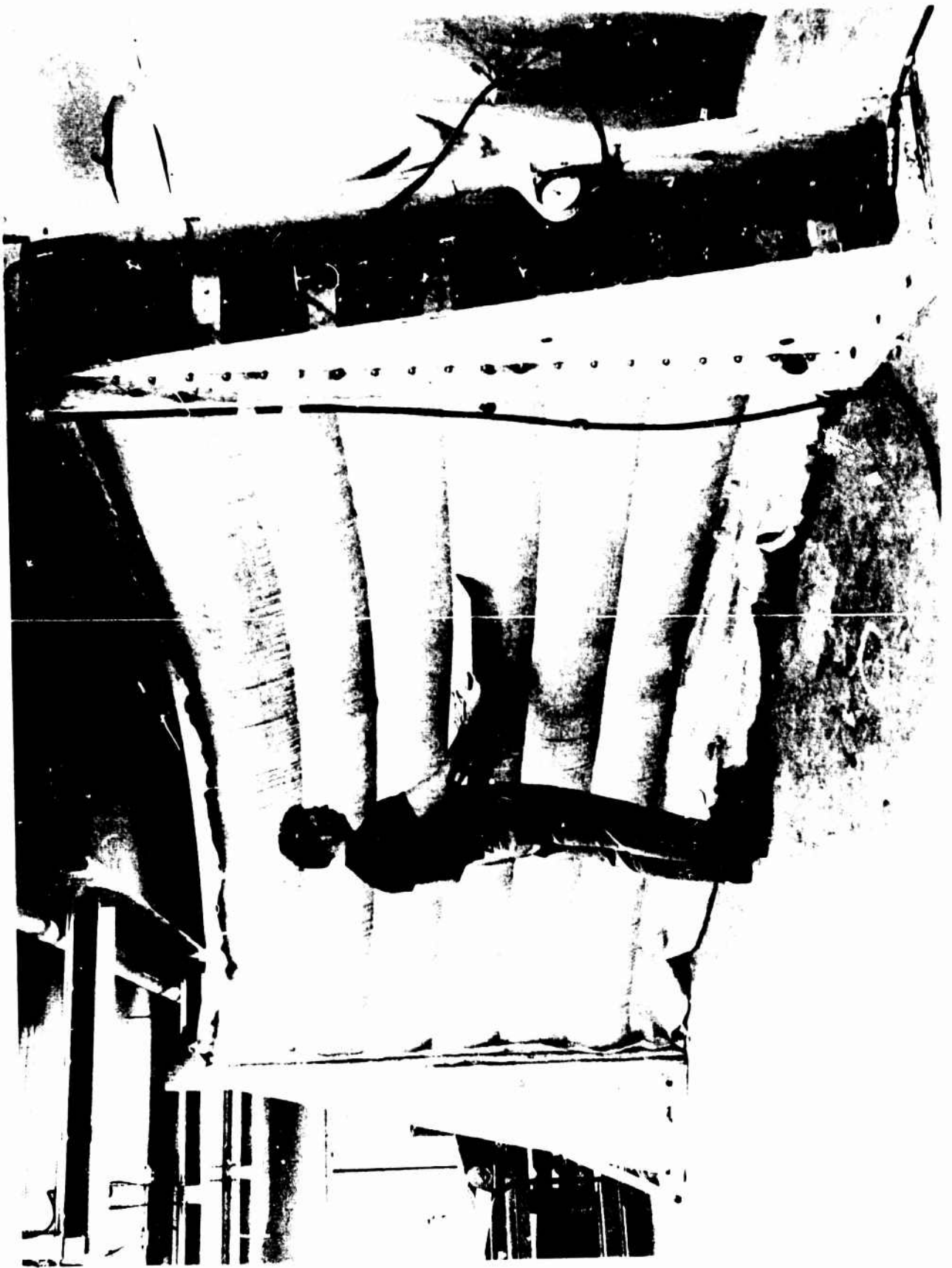


FIGURE 4: FIRST WOVEN SAMPLE OF THE INFLATABLE ARCH

The combination provided good release of the sleeve from the Neoprene latex coating and allowed the woven double wall-unit to be inflated and to remain inflated for an extended period of time. This combination was used to inflate the test section and also the full-size sections.

- 2.6.4 A special fixture was developed to support the woven arch section for spraying held at the proper arc curvature. The fixture clamped the two ends of the fabric so their faces were radial and at the correct radius when inflated.

The bladders, encased in their polyethylene sleeves, were attached to ropes and inserted into the cell openings and pulled into proper position inside the cells. The bladders were then inflated to 1.5 psi air pressure. (See Figure No. 4) and several coats of Neoprene latex were applied with the modified spraying equipment previously described.

The spray equipment worked well for days without requiring cleaning or other maintenance. The spray gun, with the proper tip, delivered a full 60-degree wet fan spray pattern. It covered the surface rapidly with good penetration of the fabric.

This unit, without further modification, was used to spray coat the full-size MUST shelter sections. The wood frame served as the basis for the design of the tooling that was made for the spraying of the full-size woven arch sections required in the fabrication of the three-section MUST shelter.

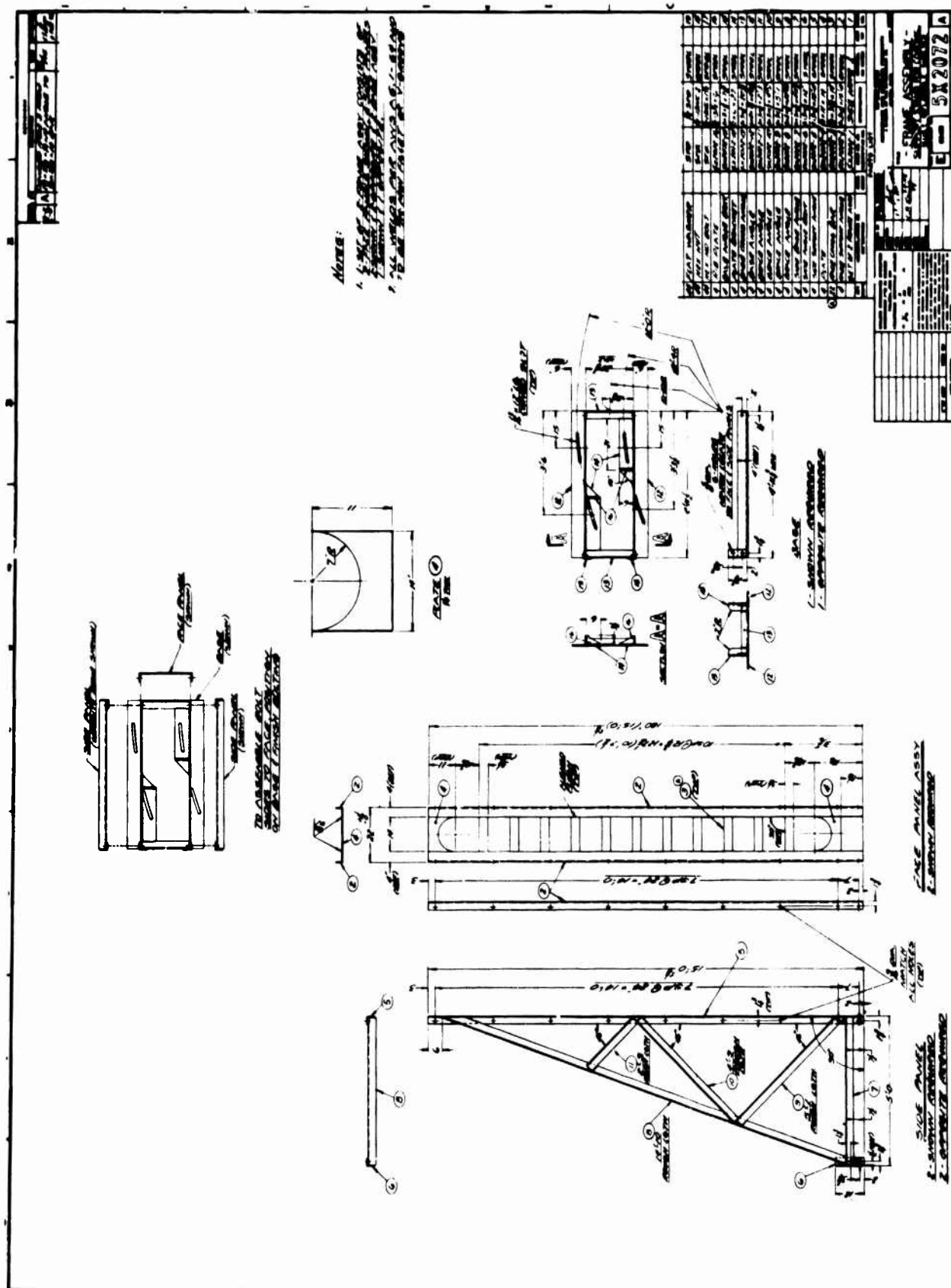
3.0 FABRICATION OF THE FULL-SIZE MUST SHELTER

3.1 Selection of a Method for Supporting Inflated Wall Section for Coating

We considered several methods of supporting the woven arch sections for coating, including various mechanized approaches. Since only three units were to be fabricated under this program, we selected a steel replica of the wood frame used to support the sample wall section during the development stage.

3.2 Design of the Steel Support Frame

- 3.2.1 B.F. Goodrich Drawing No. 5X2072-A (frame assembly, Figure No. 5) and Drawings Nos. 5X2074 and 4X2104 (facing and access covers, Figures



Nos. 6 and 7) illustrate the design of the steel support frame as it was procured. Drawing No. 5X2073 (2 of 2) shows the floor layout for this fixture and the table of X and Y coordinates representing the $\odot$ locations of section attachments. (Figure No. 8)

The frame consisted of a fabricated steel frame (Figure No. 9) with a plywood face containing the clamping arrangement to clamp the inner and outer wall of the woven arch as well as the vertical web sections. (See Figure Nos. 6 and 10).

3.2.2 A wood cover was provided for each cell opening to support the bladder when pressurized. The covers included a hole to permit the bladder inflation tube to be connected with its air supply. The covers provided a means for inserting the bladders and provided a surface against which the bladder could bear to provide a hoop tension in the inflated arch. (Figure No. 11)

3.2.3 The two support frames were fastened to the concrete floor of the work area as illustrated in Drawing 5X2073. (1 of 2) (Figure No. 12) Each base included slots that permitted some radial adjustments. The support fixtures were set up at an arc distance between the two frame sections of 37 feet 4 inches with an arc radius of 122 inches.

3.3 Preparation of the Integrally Woven Wall Sections

3.3.1 Before being installed into the frame for coating, each woven arch section was spread out on a large table and the area to be coated was precisely marked off. First a line was drawn several inches from one of the open ends by following the path of a fill yarn across the entire width of the section. Then a second, parallel line, also along a fill yarn, was drawn 37 feet, 7 inches from the first. This provided a length three inches greater than the amount to be coated as an allowance for fastening the section to the frame. The 37 feet, 4 inches length included a 4-foot allowance beyond that required for a 180° arc segment so that a sample could be cut off for tests after the coating was completed.

3.3.2 The first step in positioning the woven arch section into the support frame for coating involved suspending the unit from the ceiling of the work area at the proper radius using the clamps attached to cables from the ceiling. In the first installation, these clamp blocks were 2 inches long (Drawing 5X2073, Item 1) (Figure No. 12). We found out the weight of the woven fabric section was sufficiently concentrated at

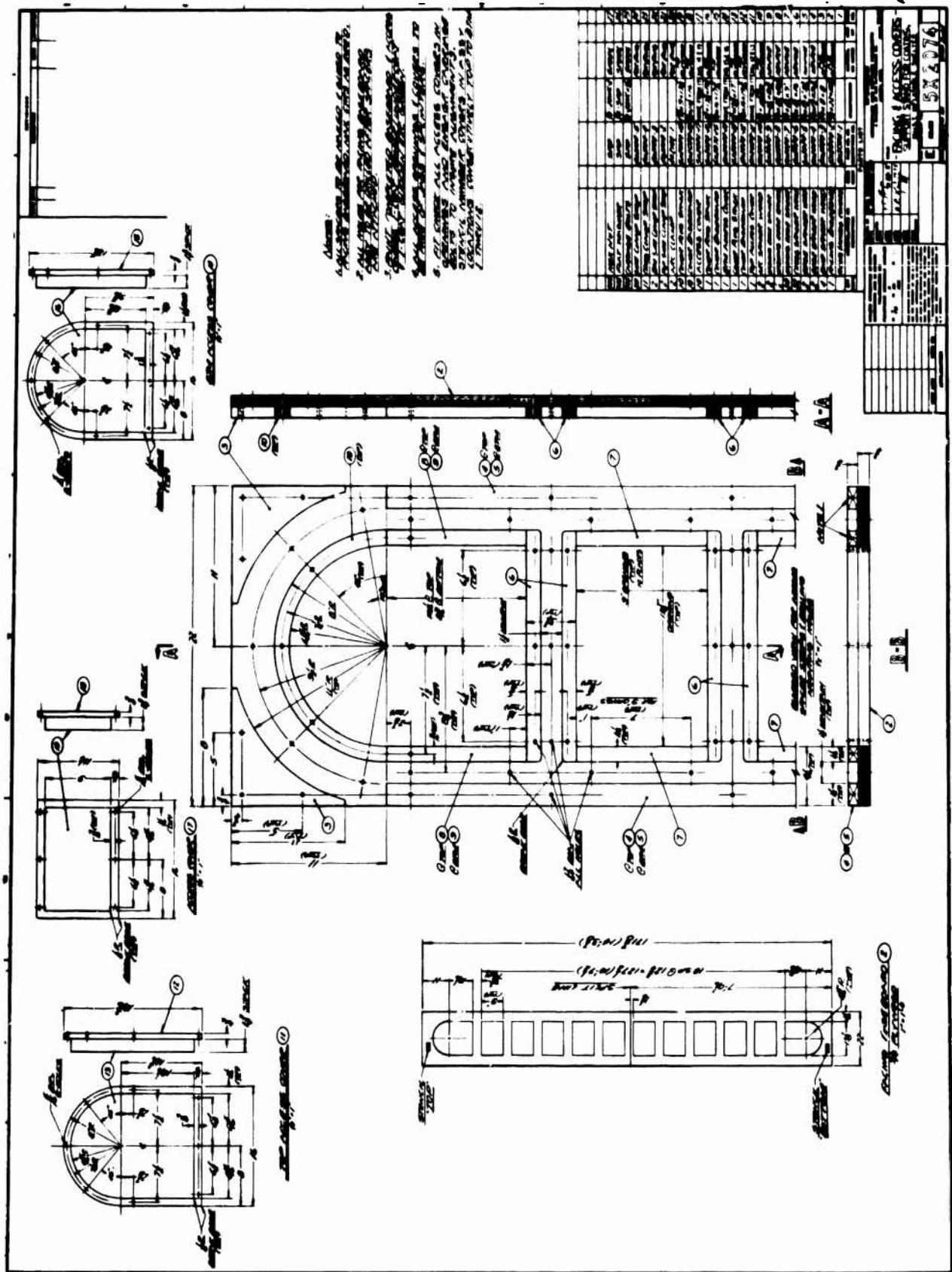
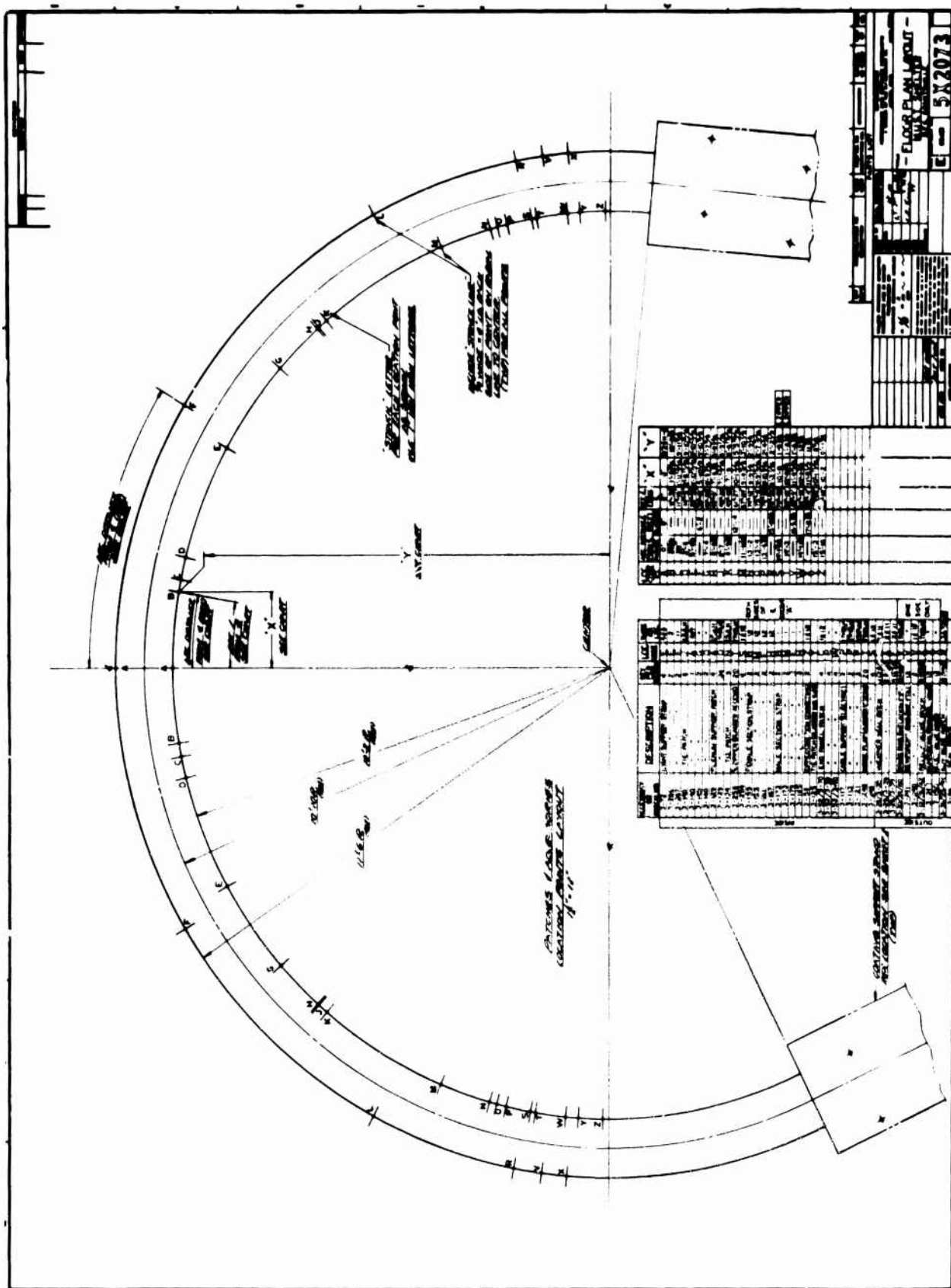


FIGURE 6: FACING & ACCESS COVERS - SUPPORT STAND FOR COATING



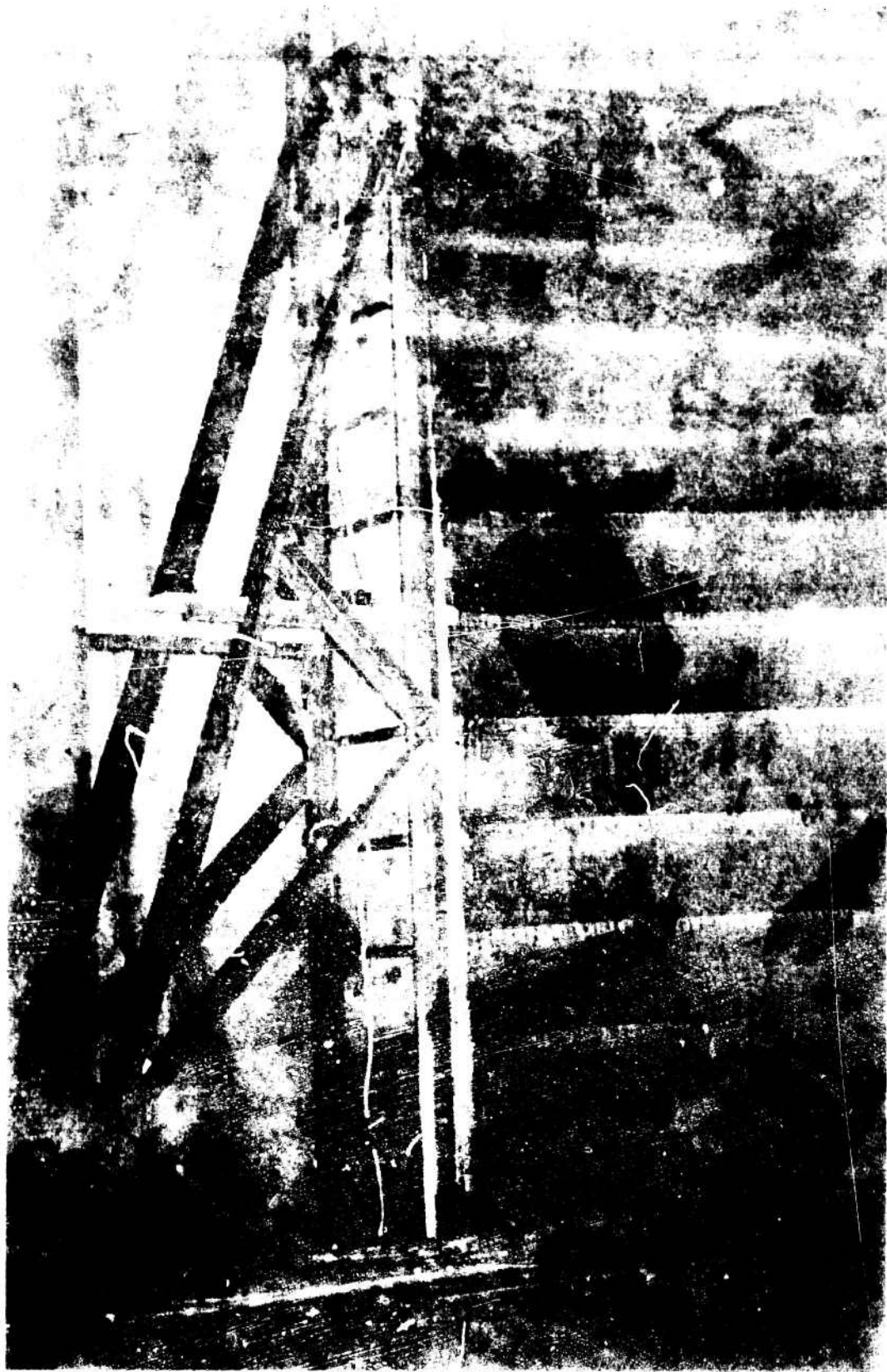


FIGURE 9 STEEL FRAME ASSEMBLY - SUPPORT STAND FOR COATING

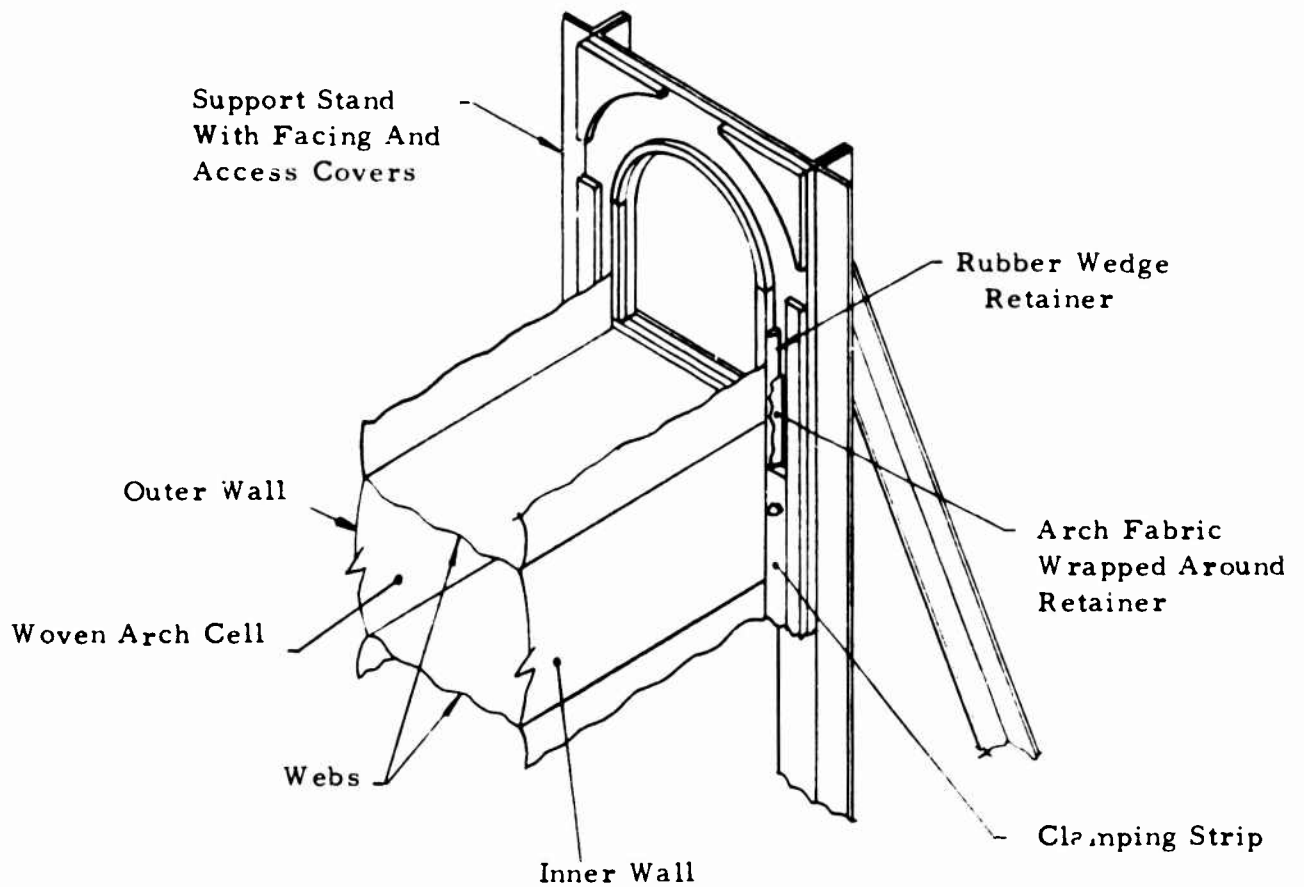


FIGURE 10: WOVEN ARCH CLAMPED TO SUPPORT STAND

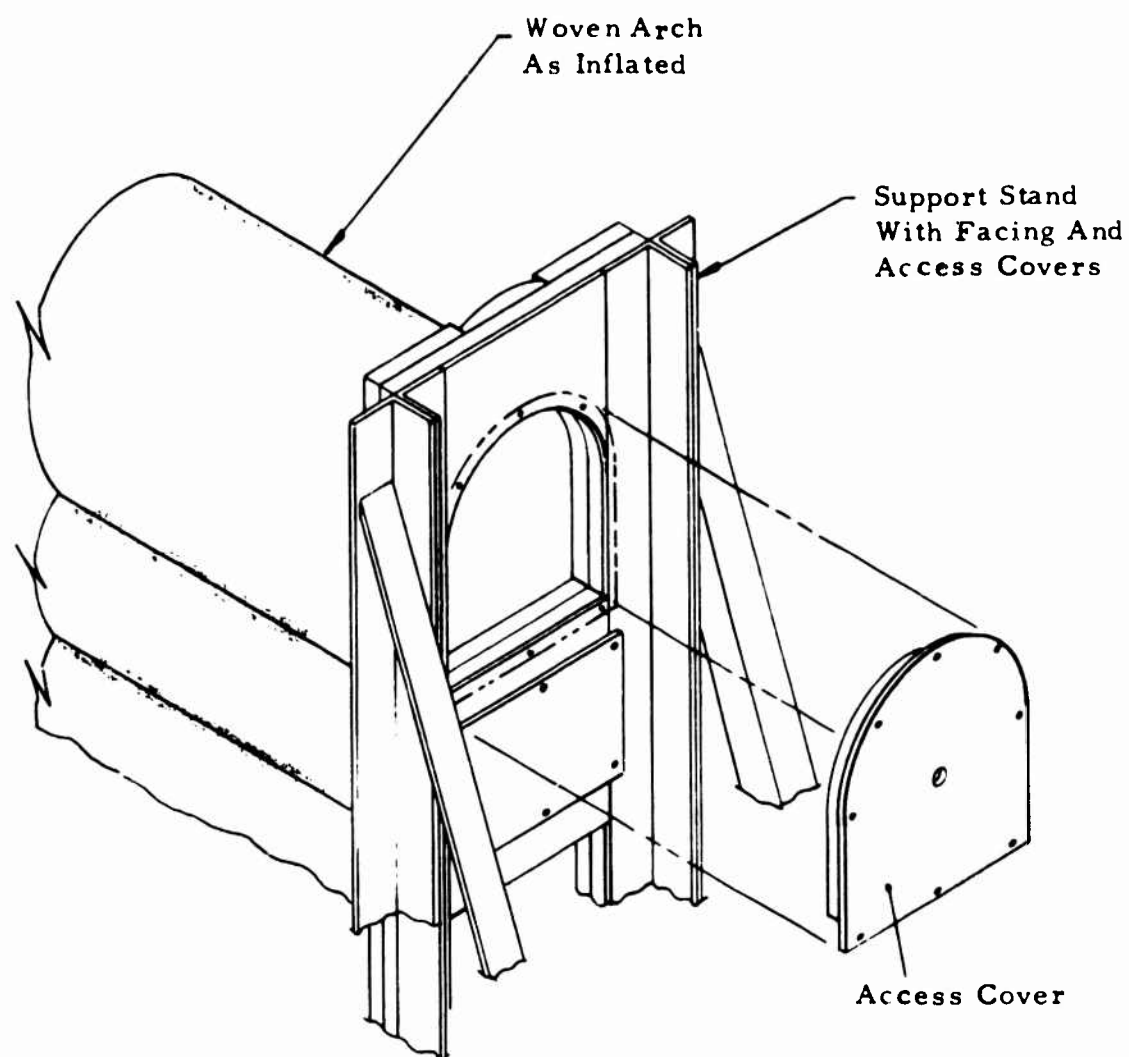


FIGURE 11: BLADDER ACCESS COVERS - BOTH ENDS

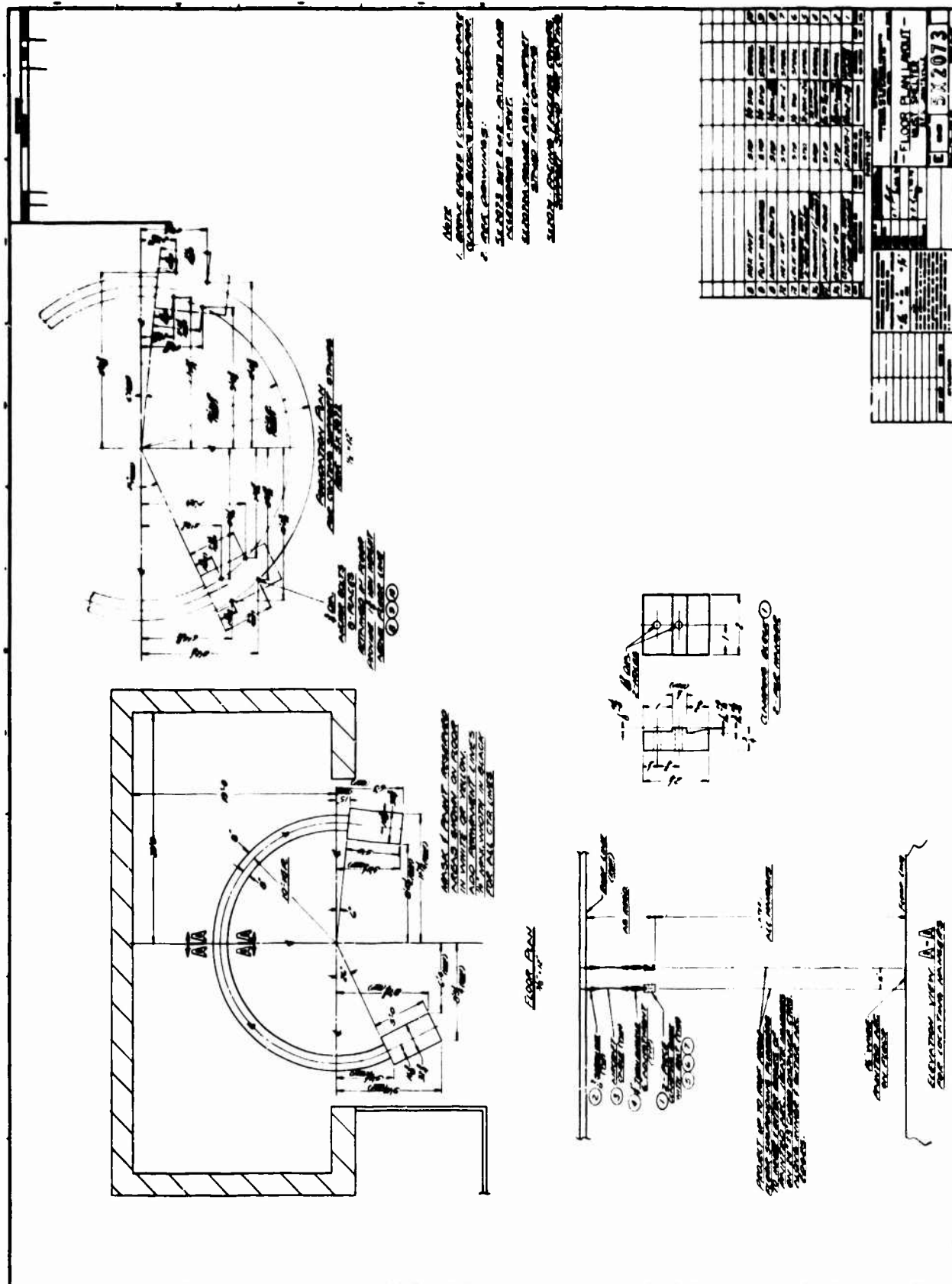
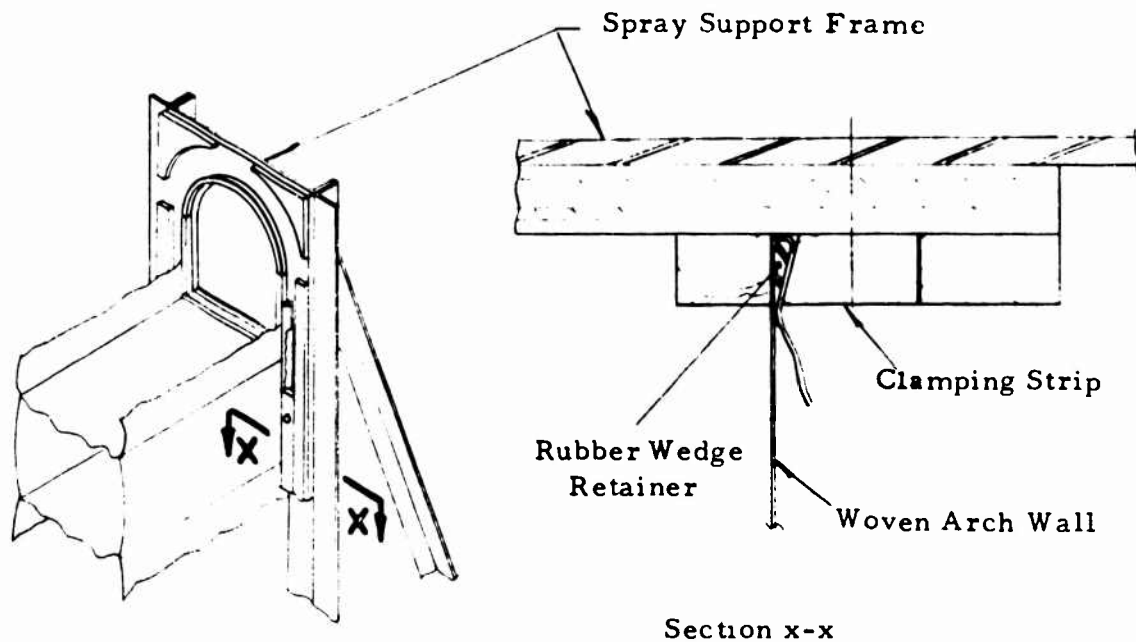


FIGURE 12: FLOOR PLAN LAYOUT

these suspension points to cause the fabric directly under each clamping block to stretch excessively, while the material on either side became wrinkled. The blocks, therefore, were lengthened to six inches to distribute the weight more evenly; thus reducing the wrinkles.

3.3.3

The open ends of the fabric were attached to the support frame by inserting the fabric into the grooves of the frame. The fabric was secured with wedge-shaped extruded rubber strip held in place by wood clamping strips which fit into the grooves and bolted to the frame. (See the sketch below)



3.3.4

Once the fabric was fastened into the frame, the excess material was trimmed to three inches long to prevent it from getting in the way while spraying. The fabric tabs which are used to support the woven arch from the ceiling must not be cut too short in the clamp area if unravelling in this area is to be prevented. We cut the tabs to 1" and found this length to present no particular problems.

- 3.3.5 The coated fabric bladders made to Drawing 5X2101 were encased in a 0.004-inch-thick polyethylene sleeve and inserted into the cells of the woven fabric by the same procedure used with the test sample described in Section 2.6 (Figure No. 13). During this operation, it is important to see that the bladders are positioned as nearly as possible into their final arched shape. Once inflated, the friction of the bladder against the wall of the fabric prevents bladder movement which makes adjustments almost impossible.

When inflated, the bladders for the two end cells, the largest in the wall unit, measured 64 inches in circumference. The other ten bladders in between measured 58.5 inches in circumference.

When inserting the bladders, we found that by starting with the center cells and working towards the ends in both directions reduced wrinkles in the wall surface. The center bladder was inserted first and inflated. Unrestricted by other bladders, this bladder formed a proper arch of the predetermined arc length, making insertion and distribution of subsequent bladders easier and more accurate. Figure No. 14 shows the inflation of the center bladder followed by inflation of the other bladders working from the center outward.

- 3.3.6 Once the bladders were inserted, wood covers were fastened over the access openings in the end of the fixture and the bladder inflation tubes were manifolded together using 0.25 inch-diameter hose. This allowed the same level of air pressure to be maintained in all the bladders. Figures 15, 16, 17 and 18 show in chronological order partial inflation, closing the access openings, and the manifolding of the bladders.

- 3.3.7 At 1.5-psi pressure, the radius of the inflated wall structure should have conformed to the design radius previously drawn on the floor of the work area between the two sections of the steel support frame. However, this was never the case because the radius dimensions of the woven arch sections were not perfect, and the polygonal shape of the bladders further prevented the formation of a perfect arc radius. Wrinkles appeared on the inner and outer wall surfaces when the arch was inflated. These wrinkles, if left uncorrected, would have caused difficulties during the spraying operation.

Since the wall section will assume the radius to which it was woven, we did not try to distort the section to conform exactly to the floor markings. Instead we concentrated on reducing the wrinkles on both wall surfaces.



FIGURE 13: BLADDER ADJUSTMENT WITHIN SECTION CELLS



FIGURE 14: INFLATION OF THE SUPPORT-WOVEN SECTION CENTER CELL



FIGURE 15: MANIFOLDING OF THE SECTION BLADDERS



FIGURE 16: INSTALLATION OF THE ACCESS COVERS



FIGURE 17: MANIFOLDING OF SECTION BLADDER -
ALL ACCESS COVERS IN PLACE

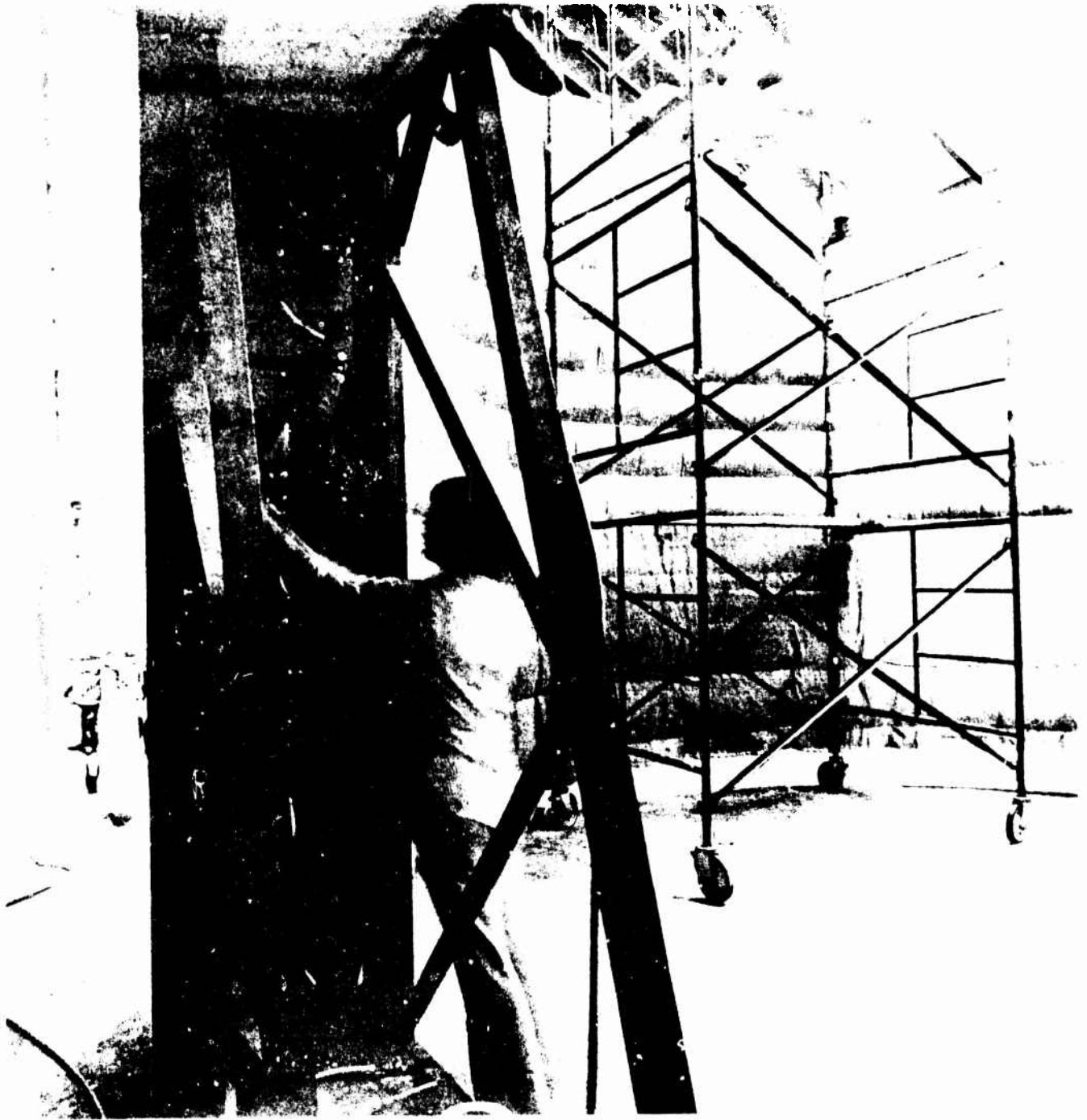
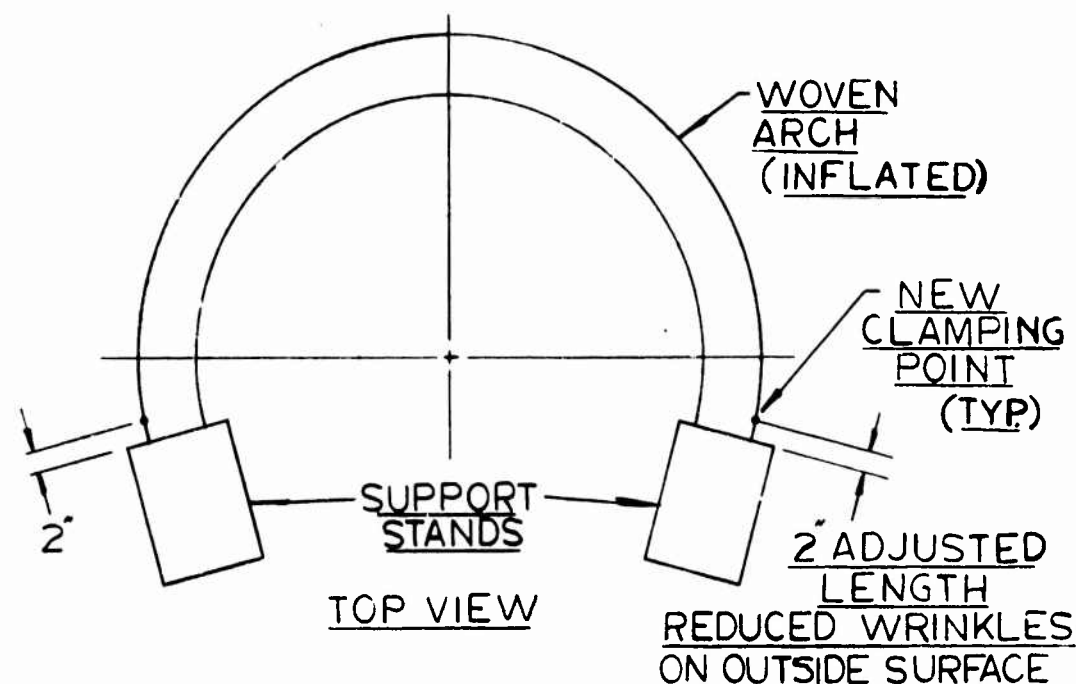


FIGURE 18: INFLATION OF SUPPORTED WOVEN SECTION -
TOP HALF

3.3.8

To reduce the wrinkles from the outer wall fabric, two inches were trimmed from each end (See sketch below). This removed a substantial amount of wrinkles from the outer wall surface.



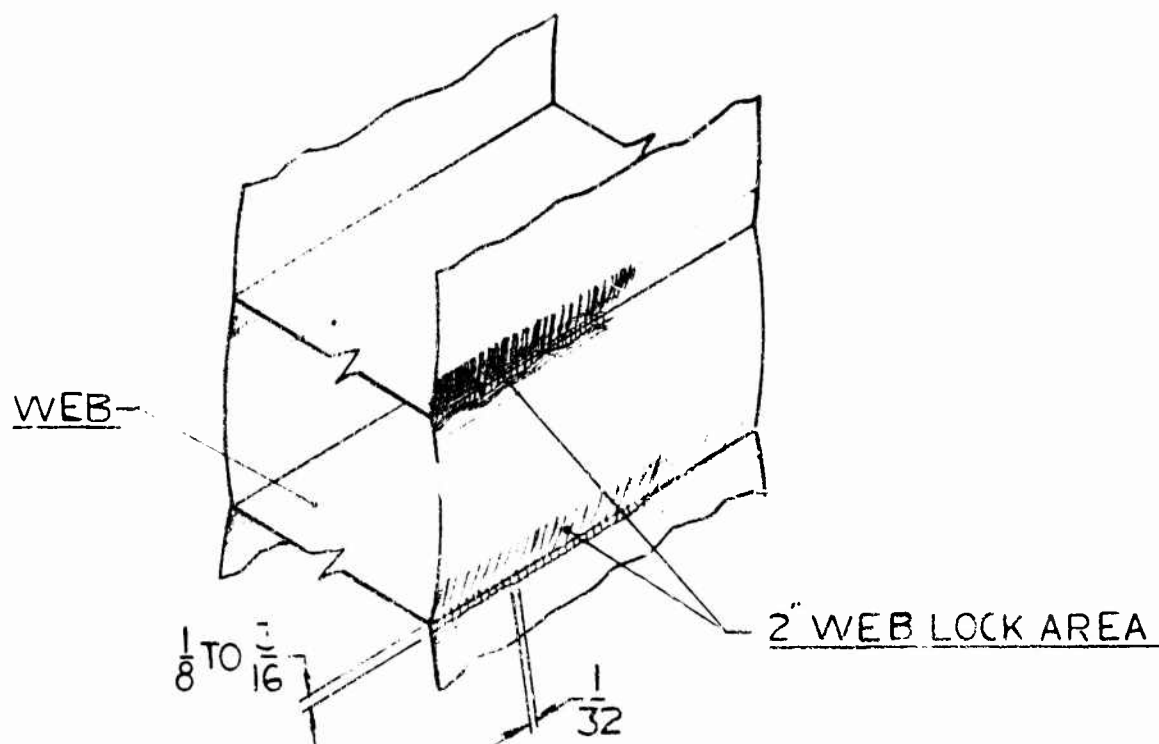
3.3.9

An attempt was made to remove the remaining wrinkles by partially deflating the wall unit, redistributing large wrinkles, then reinflating the bladders to pressure of 1.75 to 2 psi. We expected the wrinkles to disappear with this increased surface tension.

By repeating this process several times, we were able to reduce the amount and size of the wrinkles to the point where most of the remainder could be worked into the weave of the fabric by hand.

3.3.10

While trying to remove wrinkles from the wall surfaces, we discovered that increased bladder pressure (about 2 psi) produced high stresses at the joints of the wall fabric and internal webbing, causing the yarn to separate. The sketch on the next page points out these problem areas.



YARN SEPARATIONS AT WEB CONNECTIONS

This problem occurred on all three sections with the gaps measuring up to $\frac{3}{16}$ inches long and $\frac{1}{32}$ inches wide. Since these openings in the weave could not be completely covered during the spraying operation, they had to be touched up with a brush to produce a satisfactory seal as illustrated in Figure No. 24.

3.3.11

In addition to these gaps, resulting from yarn separation, the wall surfaces also contained a number of repairs made by the woven fabric manufacturer to correct imperfections in the weaving. (Figure No. 19) On the bare fabric these repairs seemed quite small, but once the Neoprene latex coating was applied they became much more prominent. Even small polyester filaments protruding from the fabric surface measured $\frac{1}{32}$ inch in diameter once they had been coated with several layers of Neoprene latex. In order to improve the surface finish, after each section had been sprayed with four or five coats of Neoprene latex, the more visible knots and yarn ends were cut off at the surface. At this point, this could be done without damaging the woven structure or reducing its structural integrity. These areas also were retouched by hand where necessary.

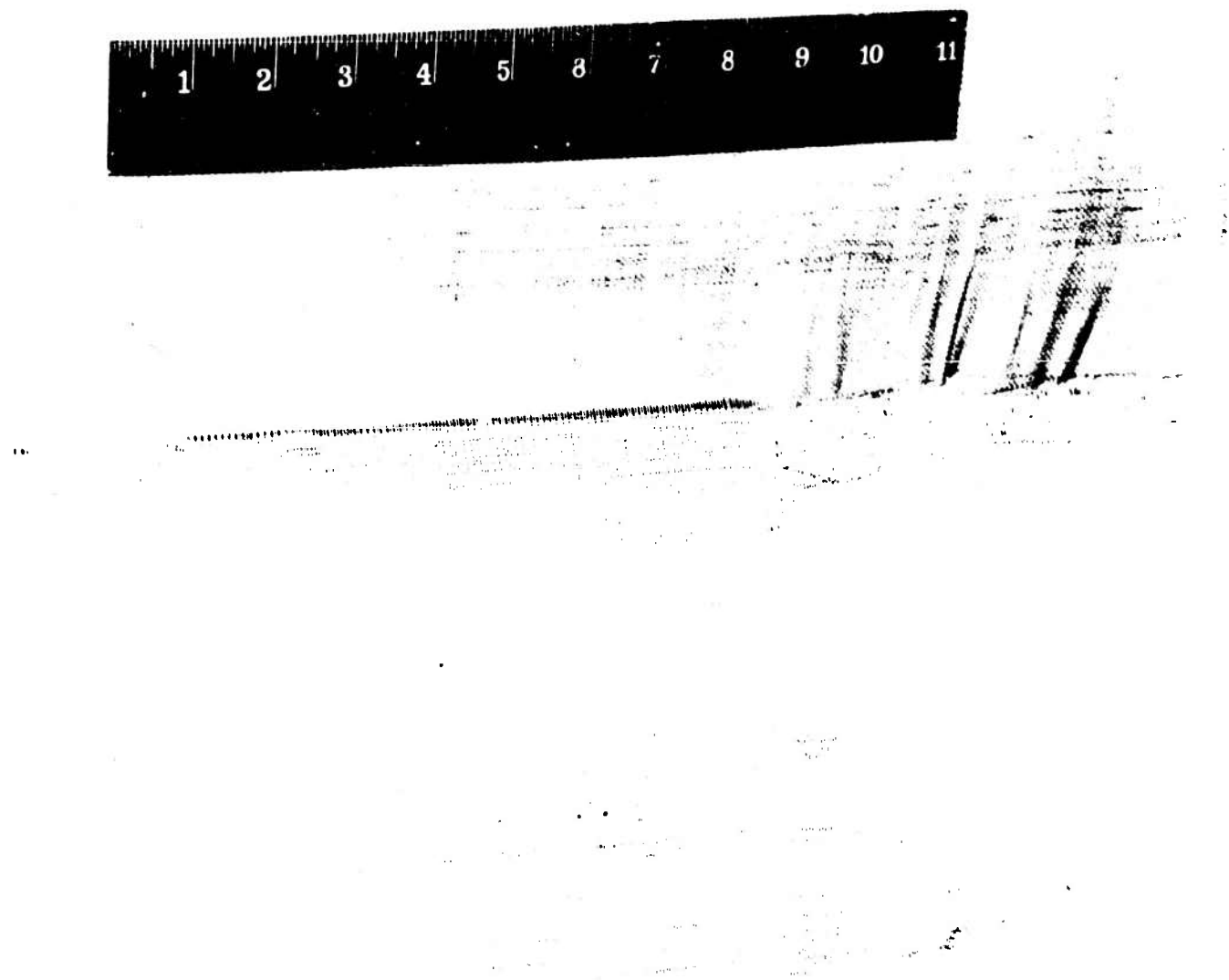
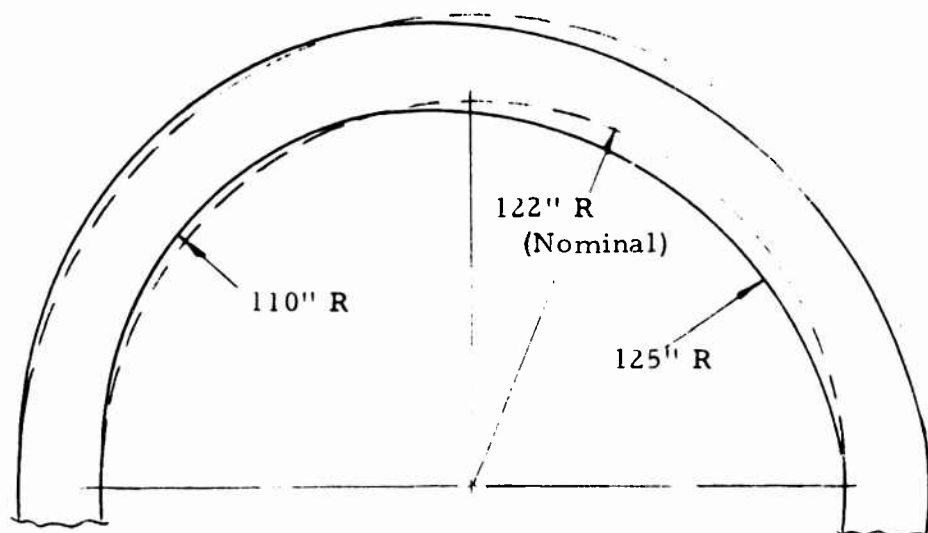


FIGURE 19: IRREGULARITIES AND REPAIRS IN THE
INFLATED WOVEN SECTION

3.3.12

One of the three wall sections, which happened to be the first to be woven but the last to be coated, also contained more discrepancies than the others. The arc radius of its inner wall was found to vary from 110 to 125 inches as opposed to the nominal 122 inches. (See the sketch below) We were not able to correct this condition.



The outer wall surface of this section also proved to be somewhat concave. (Figure No. 20). To illustrate this condition, a straight bar was held vertically against the top and bottom cells while the inflated section was in the coating frame. The distance between the bar and the wall surface varied to a maximum of 2.5 inches at the center of the section. Considerable time and effort was spent trying to correct this condition. The bladders of the center cells were allowed extra slack for endwise expansion. The clamps holding the center cell fabric to the steel support frame also were adjusted. None of these measures had any effect, so we decided to coat the section as it was

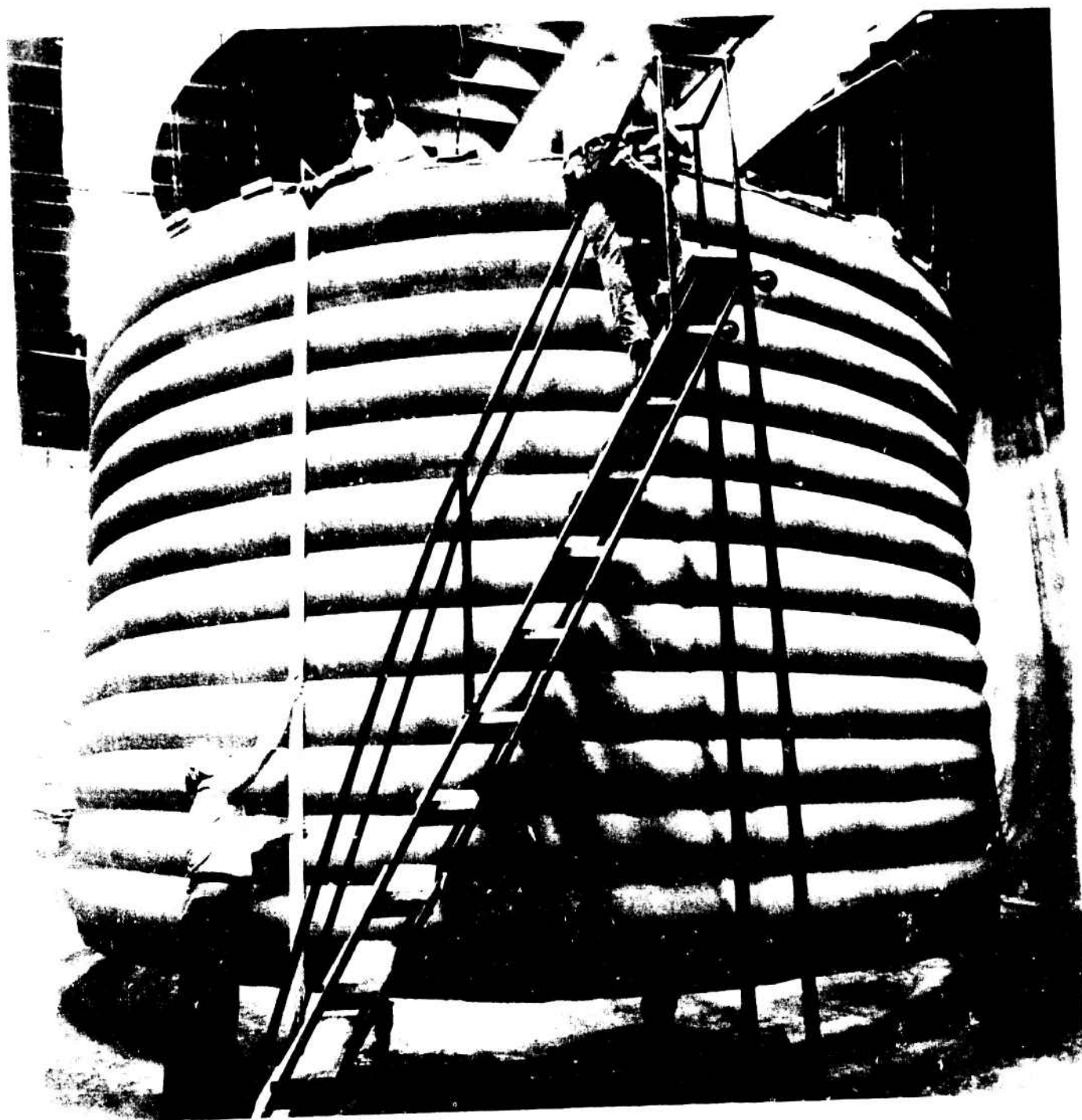


FIGURE 20: MEASURING THE CONCAVE CONDITION OF
THE FIRST WOVEN SECTION

and try to make further adjustments during the assembly stage.

This distortion, which occurred in the weaving of this first unit, was not apparent in the two subsequent sections which were more uniform and contained fewer repairs. (See Weaving Report, Appendix I for details.)

Some variation in arch radius did occur in each of the sections which can be attributed to the polygonal shape of the bladders and possibly to the uneven distribution of the bladders within the cells of the woven structure.

Before coating the first arch section, the two end support frames were moved in relation to their theoretical position in an attempt to make the arch conform as nearly as possible to the design radius which was drawn on the work area floor. The frames were then bolted to the floor, and the woven structure was ready for coating. This adjustment brought the inflated arch more nearly into the true radius.

3.4 Coating the Full-Size Inflatable Woven Structure

3.4.1 The full-size arch sections were coated with the Neoprene latex compound 120X-63112A, which is the same material that was used to coat the sample unit as described in Section 2 of this report.

3.4.2 The equipment used to coat the sample unit (See Section 2.6) also was used without modification to coat the full-size woven arch structures. (See BFG Drawing No. 5X2082, Figure No. 1 and Figure Numbers 2, 3, and 21.) A standard carbide tip with a 0.017 inch orifice was mostly used throughout the spraying operation.

The equipment worked well, surface coverage was good, and the delivery rate surpassed our expectations. At the prevailing atmospheric conditions (temperatures of 70° to 80°F and 65 percent humidity), we were able to apply a coat of the Neoprene latex compound over both the inner and outer surface in less than 30 minutes. A sprayed coat required about 60 minutes to dry sufficiently to permit the application of the next coat. On occasion, the humidity exceeded 80%; and as a result, the drying took up to two hours per one coat even with a high volume fan running in the work area.

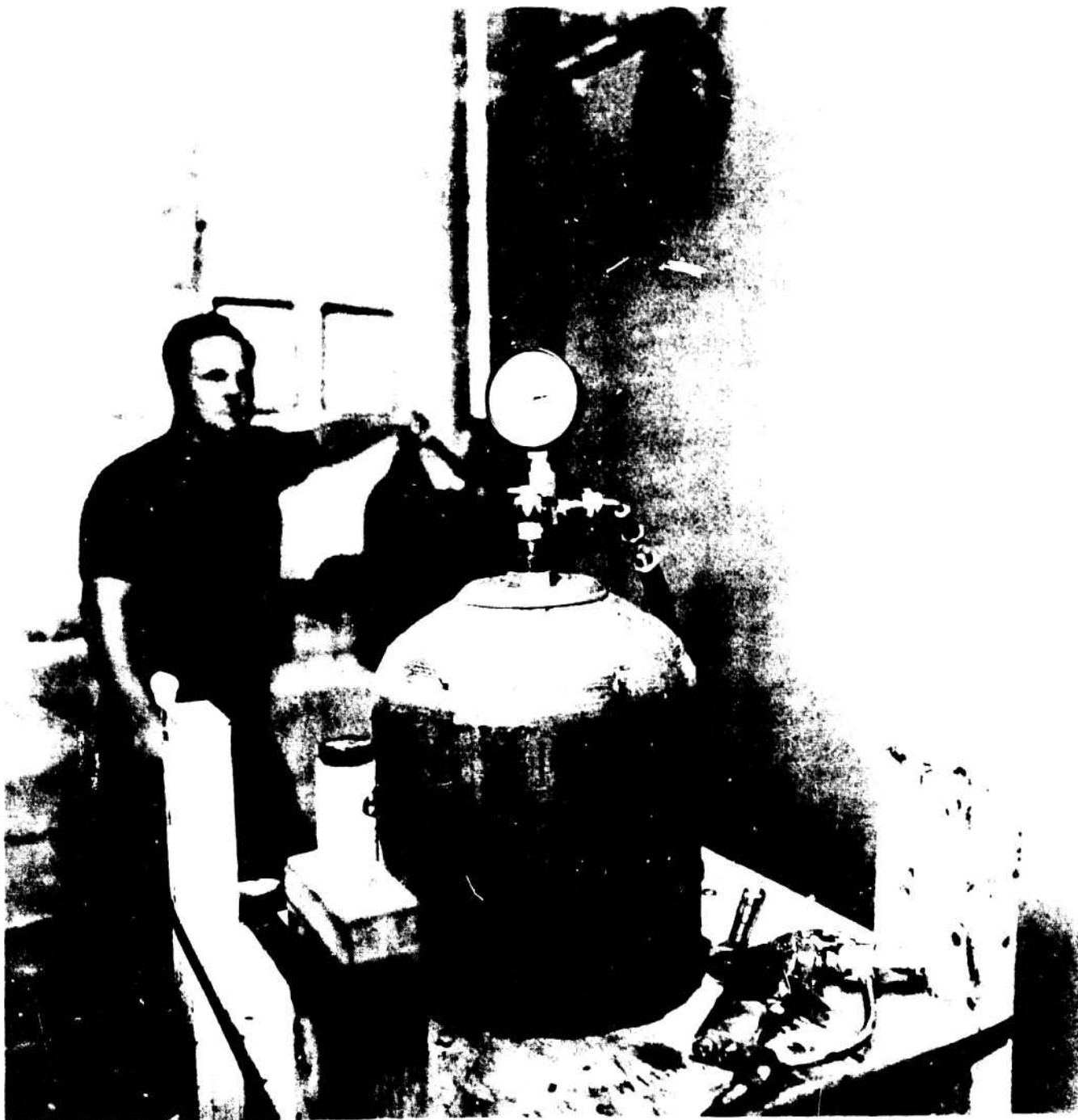


FIGURE 21: SPRAY EQUIPMENT READY FOR USE

- 3.4.3 Each spraying operation was started using a pressure of 2650 psi on the Neoprene latex supply tank which is the normal pressure of the standard "T" size nitrogen bottle. For best results, accumulator pressure was maintained between 2000 to 2500 psi, although satisfactory spraying was possible with pressures as low as 1500 psi. With this lower pressure, smaller orifice of the gun tip was required to properly atomize the Neoprene latex.

The spraying technique itself was similar to that used for spraying ordinary house paint. The gun was held 12 to 15 inches from the surface and moved back and forth horizontally, parallel to the surface being sprayed. The motion was kept as uniform as possible taking care to avoid overlapping the sprayed areas, which would have caused spray runs. A person with average skill can master the operation in 10 to 15 minutes.

Figure Nos. 22 and 23 show spray up operation of section - lower and center portions.

- 3.4.4 After the first coat of the Neoprene latex had been applied, the gaps caused by yarn separation at the wall and webbing joint (See Section 3.3.10) were filled in by brush. Similar treatment was given in areas where gaps occurred due to weaving imperfections. (Figure No. 24).
- 3.4.5 To spray the area of the outer wall surface which could not be reached from the floor, a movable step ladder was used. (Figures 25 and 26). A helper then moved the ladder along the wall as the spraying progressed. To spray the woven inside wall of each section, fixed scaffolding with platforms at several heights were used.
- 3.4.6 The second through the sixth coats of the Neoprene latex compound were applied in the same manner as the first. Between each coat, the gaps caused by yarn separation were filled in with a brush.
- 3.4.7 After the sixth coat, a visual inspection of the wall surfaces revealed some pinholes that probably could not be filled by the last two coats of the Neoprene latex compound. It was estimated that four or five additional coats of Neoprene latex would be required to fill these holes. Neoprene latex was brushed into the voids several times, and the seventh and eighth coats of the Neoprene latex were sprayed on extra thick.



FIGURE 22: SPRAYING OF INFLATED WOVEN SECTION LOWER CELLS
OUTER WALL



FIGURE 23: SPRAYING OF INFLATED WOVEN SECTION CENTER PORTION
OUTER WALL



FIGURE 24: NEOPRENE-LATEX APPLICATION BY BRUSH
IN THE CELL-WEB JOINT

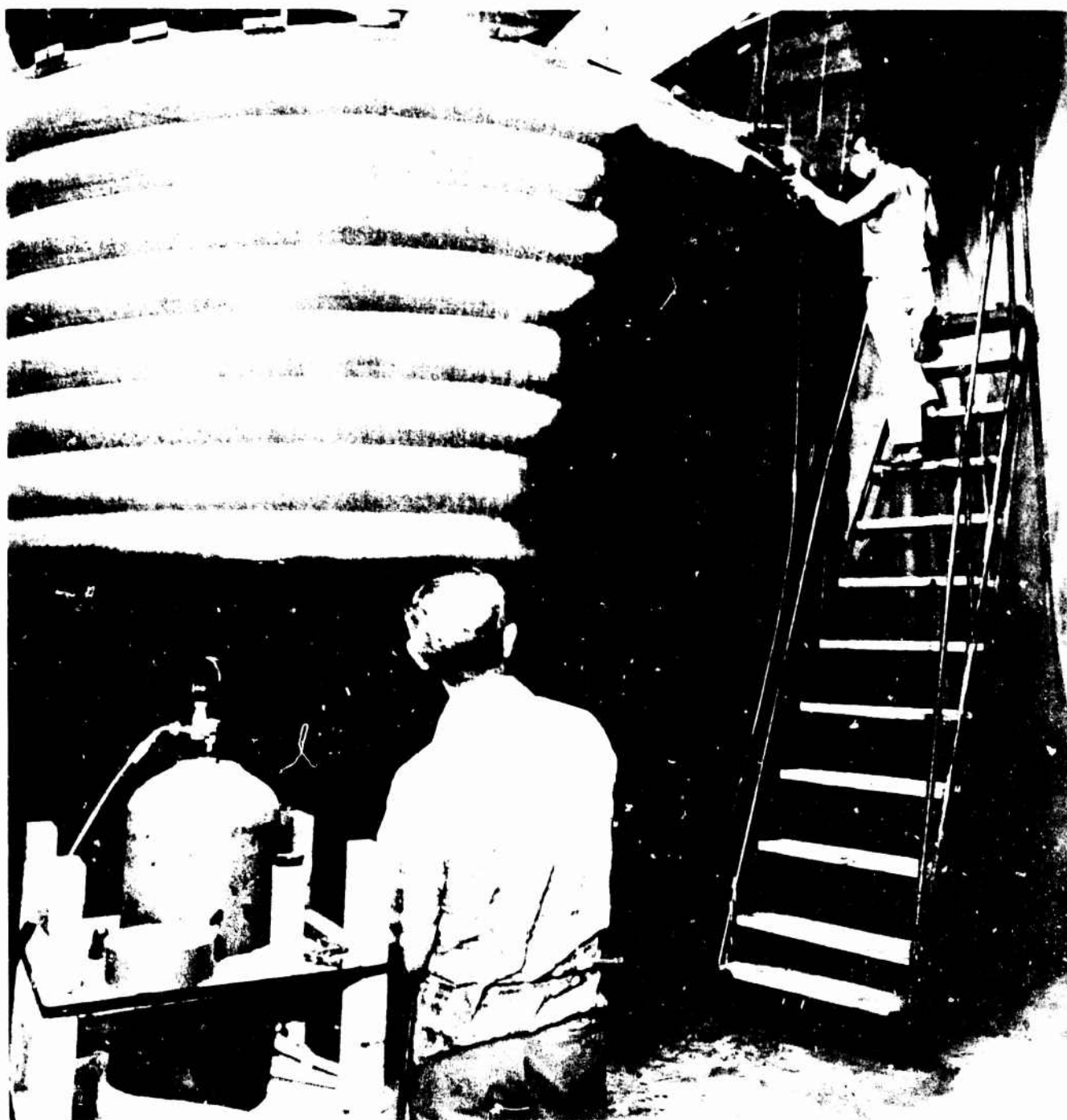


FIGURE 25: SPRAYING OF INFLATED WOVEN SECTION TOP CELLS
OUTER WALL - USING MOVABLE STAND



FIGURE 26: COMPLETION OF NEOPRENE LATEX SPRAY OPERATION

- 3.4.8 After application of the eighth coat of the Neoprene latex compound, the inflated woven structure was allowed to dry for 24 hours before the application of Hypalon top coats.
- 3.4.9 To provide a neutral surface for the colored top coats of Hypalon, we first applied a white ground coat of A 625 B "Radalon" mixed with A 1202 B as a curing agent in a ratio of 32 to 1. "Radalon" is the B.F. Goodrich trade name for a weather-resistant Hypalon coating designed for spray application.
- 3.4.10 To apply this material, we used standard air-atomized DeVilbiss spray equipment, which was on hand. The atomizing air pressure used was 70 psi while container pressure was maintained at 30 psi. We encountered no difficulties in this spraying operation, but proper ventilation had to be maintained at all times because of toxic fumes since tuluol was used as a solvent in the coating material.
- 3.4.11 No surface preparation was required before applying the white Hypalon ground coat. One heavy coat completely covered the black Neoprene surface. This surface required no further preparation prior to applying the colored top coats.
- 3.4.12 For the top coat on the outer wall, B.F. Goodrich Compound 0500 BH 272 was used which is an olive drab coating which meets the physical requirements for this application, including Federal Color Standard #595. For the inside wall, B.F. Goodrich compound 0500 BH 273 which is pale green was used.
- 3.4.13 The viscosity of these compounds was identical to that of the white undercoat. The same spray equipment with identical atomizing and cup pressures was used for their application.
- 3.4.14 We encountered no difficulties in spraying these materials. One heavy coat or two light coats completely covered the white undercoat and gave a satisfactory color. On the average, one gallon covered 150 square feet of surface.
- 3.4.15 The surfaces dried to the touch within 30 minutes, but we allowed a minimum of two days before bonding the various attachment to the sprayed surfaces. After this final spraying operation, the thickness of the coated fabric in the walls ranged from 0.034 to 0.036 inches. The fabric itself accounted for 0.017 inches, with the eight coats of Neoprene latex and the two coats of Hypalon accounting for the rest. We

considered this sufficient for weather and abrasion resistance as well as for bonding hardware and other attachments.

- 3.4.16 Although the contract did not require first article approval, we were required to coat one-half of the first woven arch structure. Then we were to obtain approval from U.S. Army Natick Laboratories' technical representatives before proceeding with the spraying of the balance of the first section.

On April 22, 1975, D. Shaw and S. Shurtleff inspected the partially coated first section and gave their approval of the coating and released us to complete this section as well as two additional sections required by the contract.

- 3.4.17 The second and third inflatable woven structures were coated using identical procedures as were used on the first section.

3.5 Marking of Inflatable Section

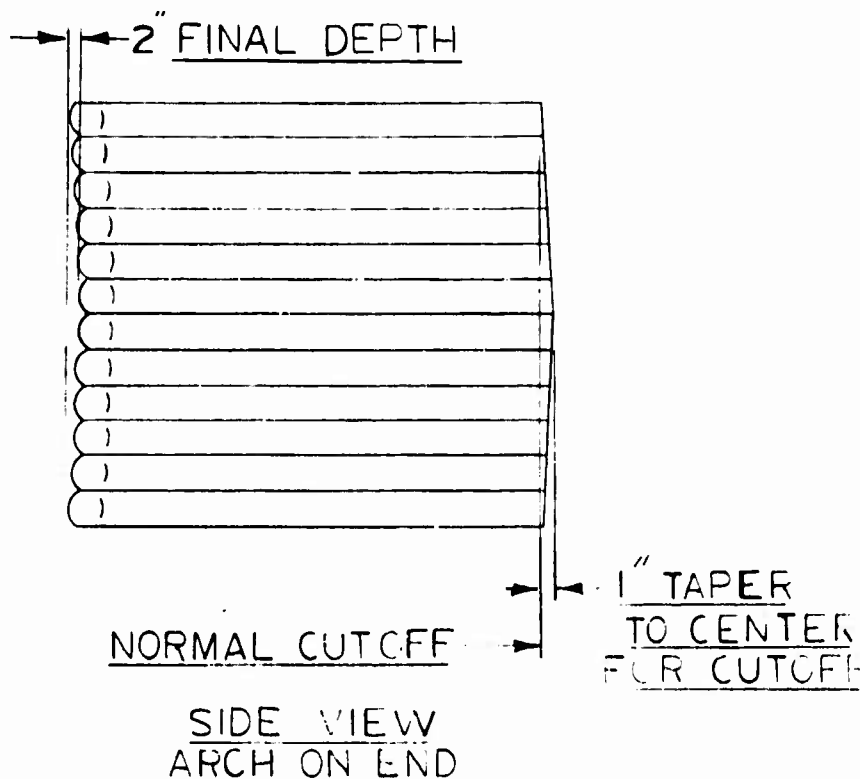
3.5.1 Location of Reinforcement and Hardware

In describing the installation of the woven arch structure into the spray support fixture in paragraph 3.3.7, it was pointed out that the arc radius of the inflatable arch did not correspond to the theoretical radiuses drawn on the factory floor. For that reason, we could not project these points onto the surface of the coated arch sections as originally planned. It became necessary to establish all locations by measuring on the surface from a centerline. BFG Drawing 5X2073 (2 of 2). See Figure 8 for location of the various attachments that were bonded.

- 3.5.2 The location of the various attachments are given in the accompanying tables as arc distance from the Q_L and as X and Y coordinates. With the use of plumb bob, the vertical centerline of the structure was marked and from this Q_L along the inner and outer web radius the arc distances of each location point was established. Using a plumb bob, parallel vertical lines were obtained. At proper vertical height, a mark was made to locate the patches and hardware. Location of the cutoff points for the inner and outer walls were obtained in the same way. These dimensions for the cutoff points correspond to the arc lengths given for a structure made the conventional way. All the dimension lines were established with the structure inflated to its normal inflation pressure of 1-1/2 psi.

3.5.3 As stated in the Paragraph 3.3.12, the last arch section when inflated was found to be concave.

In order to reduce the 2-1/2" distortion in the arch, the cutoff points were measured on the surface and 1" additional length on each side of the centerline was added to the middle of the arch to assure the arc length in this area. See the sketch below.



This adjustment reduced the concave depth by 1/2".

3.6 Bonding of Patches & Reinforcements

3.6.1 The fabrication of patches, reinforcements, and hardware which were adhesively bonded to the arch sections had been completed using the standard specification materials as specified by the LP/P. DES. 42-70 and corresponding U.S. Army drawings. Therefore, their fabrication will not be described in this report. Some patches, whose dimensions have been changed, were redrawn and identified by marking with the corresponding U.S. Army item numbers in the parentheses. []

- 3.6.2 Having previously determined the exact location where the various parts were to be bonded, the areas were wiped clean with solvent and abraded with 80-grit sandpaper. Two coats of adhesive were applied over an area 1/4" larger in all directions than the patch size. The adhesive was also applied to the patch surfaces after they had been properly cleaned and abraded. After the second coat, five minutes drying time was allowed before the patches were applied and rolled down. (For details, see Evaluation Report.)
- 3.6.3 Most of the patches were applied while the arch structure was inflated to its normal operating pressure of 1-1/2 psi while still in the spray stands. (Figure No. 27).
- 3.6.4 It should be pointed out that all the patches which were applied to the first inflatable structure were bonded with Staley Chem. Co. Adhesive N-136-B and A. This same adhesive was used for the end panels and in the fabrication of the bladders. On May 21, 1975, the use of this adhesive was discontinued after tests showed that the Bostic 1039 with Boscodur #5 accelerator provided better physical properties at elevated temperatures than the N-136-B and A adhesive.
- 3.6.5 All adhesive bonds on the second and third sections and the connecting straps of the first section were completed using the Bostic adhesive.
- 3.6.6 After the patch bonding was completed, the inflated section was kept inflated for 24 hours. Thereafter, the bladders were deflated, access covers removed, and the bladders and polyethylene sleeves were pulled out of the cells. Difficulties were encountered in removing the polyethylene tubes because of cohesion to the Neoprene. This problem was solved by attaching the polyethylene tubes to the end of the bladder and pulling the bladders out. In that way, the separation of the polyethylene sleeve from the inner surface of structure walls occurs in a peel fashion.
- 3.6.7 The polyethylene tubes were used only once because they were distorted in removing them from the cells. However, the same bladders were used during the spraying of all three sections.
- 3.6.8 The wooden clamps and the rubber extrusions were then removed, thus releasing the coated structure from the support stands.
- 3.6.9 The coated woven structure was then removed from the stands and taken to the work area where the final assembly was to take place.

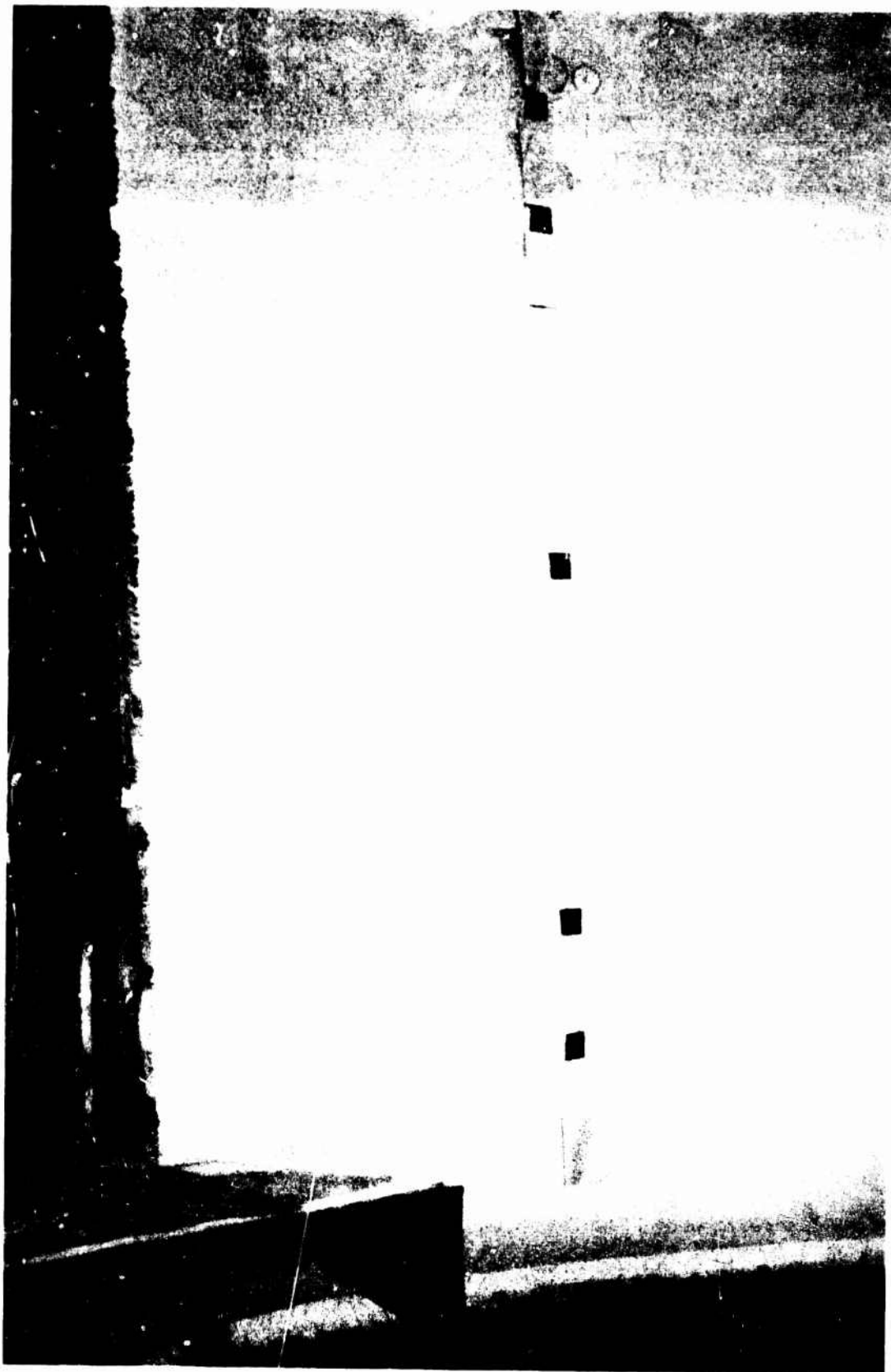
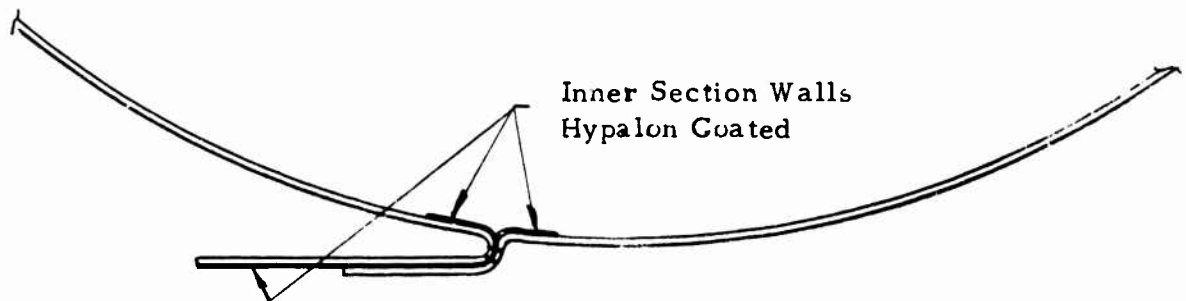


FIGURE 27: BONDING OF PATCHES ON INNER WALL
SECTION INFLATED IN THE SPRAY SUPPORT STAND

- 3.6.10 Using the previously marked lines, the ends of the coated portion were cut to final size. The excess material removed was used for sample fabrication and tests. A section of this coated material was sent to Natick Laboratory for their use.
- 3.6.11 Twenty horizontal and four vertical slots were cut at proper locations on the structure inner wall. In each slot, a 10"-long zipper was bonded. Through these zipper openings, the bladders are inserted or replaced.

To obtain a good structural bond, a coat of Hypalon was brushed on the inner surface adjacent to the zipper slot. The zipper patches were made with a double flap so when bonded in place the attachment was in double shear.

- 3.6.12 The inner surfaces of the open ends of the bottom legs of the arch were coated with Hypalon in order to obtain good adhesion when the ends were closed by sewing followed by adhesive bonding. (See sketch for the illustration of the coated areas.)



- 3.6.13 At the same time, an adhesive coating was applied to ends of the webs. This adhesive application was done to prevent ravelling of the web fabric. (Figure No. 28).



FIGURE 28: PREPARATION FOR BONDING AND SEWING OF SECTION OPEN END

- 3.6.14 At the proper location on the outer surface of each cell, openings were cut for the 12 pressure relief valves and 12 check valves. The inside surface of the cells were Hypalon coated adjacent to the valve openings in order to obtain a good seal of the brass rings to which the valves were bolted. (Figure No. 29).
- 3.6.15 The open ends of the inflatable structure were closed by sewing, using a double-needle stitch in the straight section followed by inserting and sewing in a pattern cut piece of coated fabric to form the hemispherical ends in the outermost tubes. This activity was somewhat cumbersome because the bulk and weight of the coated structure had to be handled while sewing.
- 3.7 Preparation and Insertion of Bladder Into the Inflatable Structure
- 3.7.1 The reliability of the entire inflatable structure depends not only on the integrity of structural walls but also on the inflation bladders, which rigidize the structure. The permeability of coated fabric used in the bladders must be as good as possible. The workmanship and the adhesive bonds used in their fabrication had to be of a high quality to obtain near zero leakage rate.
- 3.7.2 The design of the bladders differs from the conventional bladder used in the standard MUST shelter in that they were fabricated from 13 identical segments, which when bonded together formed an arched tube of polygonal shape. The end closures of the tubes were made in a manner similar to that used in the present conventional design.
- 3.7.3 Each tube was fitted with an inflation check valve and pressure relief valve then pressurized to 2.0 psi to test for leakage. The bladders maintained their shape well, did not leak and the permeability was negligible. In 24 hours, the tubes did not loose more than 0.3 psi pressure. The inner radius of the various bladders was between 120" and 125", which is well within the drawing tolerances. The BFG Drawings 5X2101 and 2113 shows the detail of the bladder and its end closure. The coordinates are given for the bladders for the outermost structure cells whose circumference is 64" as well as the inbetween cells which have a circumference of 58.5".
- 3.8 Insertion of Bladders Into the Section Cells
- 3.8.1 Each section requires 12 bladders of which the two outermost are larger in diameter than the remaining ten. For ease of distinction, the larger two were made from an orange coated fabric, and the other

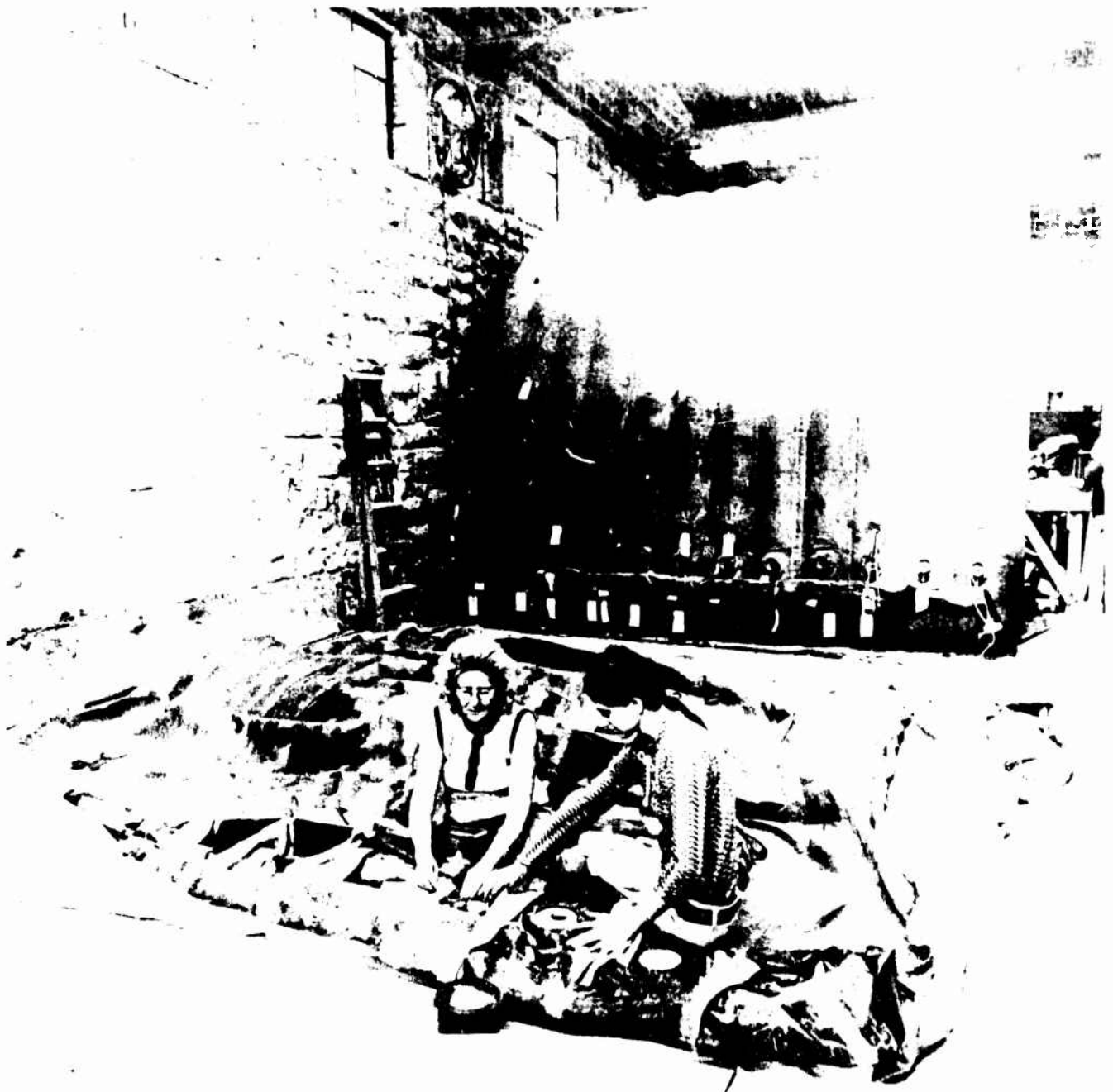
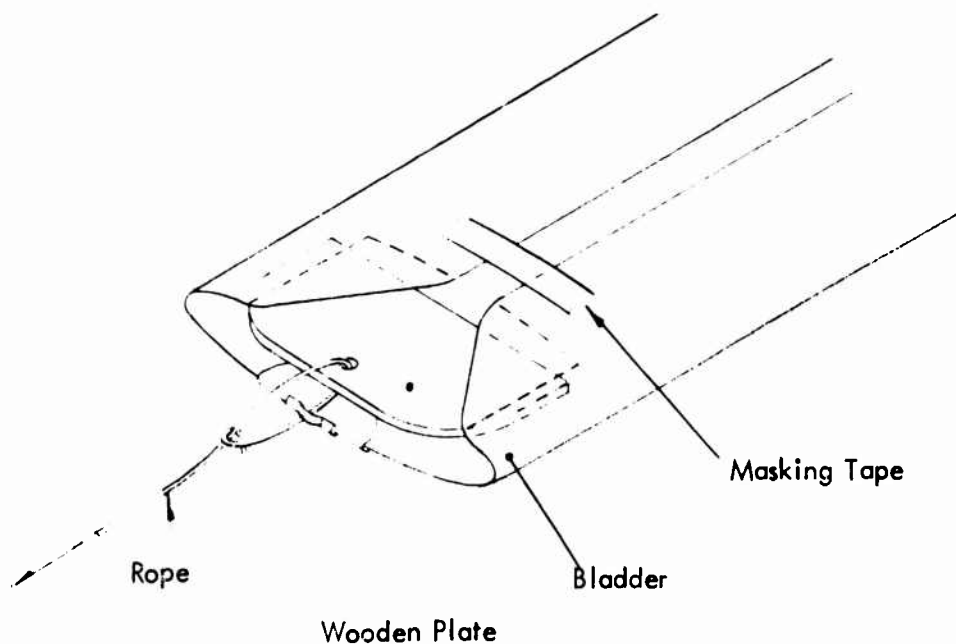


FIGURE 29: INSTALLATION OF CHECK VALVES BRASS RING
OUTER WALL SURFACE

ten from black colored coated fabric.

- 3.8.2 After each of the bladders were given a 24 hour leak test, the check valve was marked for rotational alignment then disassembled from the bladder. Valve removal is required in order to insert bladders into the cells, since the check valves will not pass through the brass flange ring installed on the outer section walls. The valve must be removed and then remounted after the bladder is inserted and aligned.
- 3.8.3 The coated section was then stretched out on the floor with the inner surface (pale green) facing up.
- 3.8.4 Ropes 40 feet in length were fed through the zipper openings into each section cell. At the end of each rope a bladder was fastened and carefully fed through the zipper opening. Two persons were required for this operation; one, for pulling the rope; the second, for feeding the bladder into the zipper opening. To prevent bladder rotation within the cells, the end of the bladders were fastened to a 1/2" thick 12" by 6" wooden plate and then pulled through with the rope as shown in the sketch below.



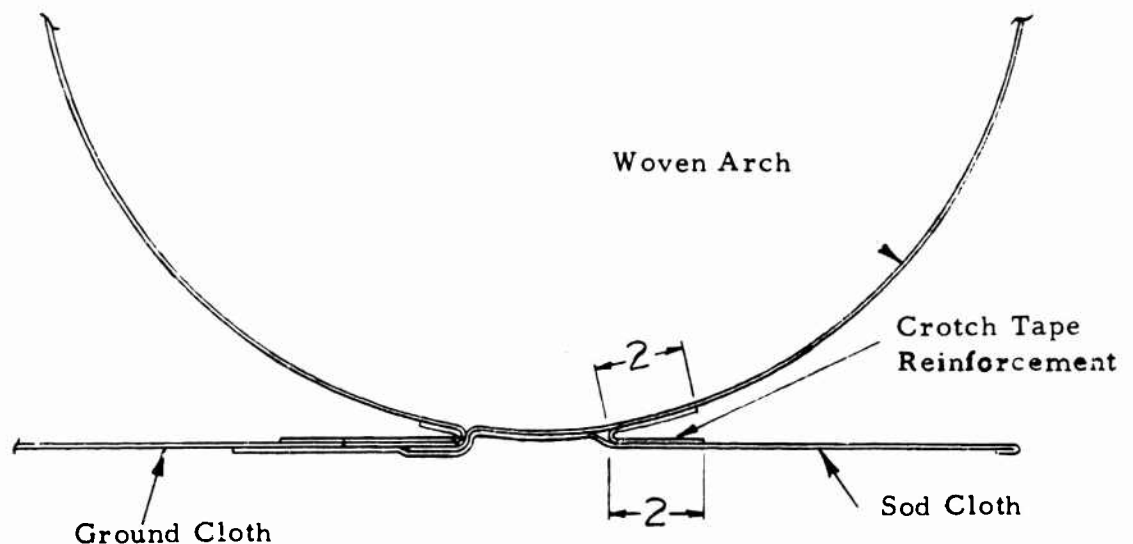
Careful feeding into the cell zipper opening was required to prevent bladder rotation even with the wooden guide plate. Attention was given to assure that the direction of the bladder curvature corresponded to the curvature of the wall.

3.8.5 Once in place, the check valves were attached to the bladders and the outer wall.

3.8.6 With the bladders installed, the assembled section was stretched out as much as possible to distribute the bladders uniformly within the cell's length. Uniform distribution of excessive bladder length will result in fewer wrinkles in the wall surfaces, once the section is inflated.

3.9 Bonding of Sod Cloth to the Coated Section

3.9.1 The sod cloths shown in BFG Drawing 5X2098, Part No. 3 and 4 are adhesively bonded to the bottom of the arch section. They are reinforced with a 4" wide crotch tape where the cloth is tangent to the bottom radius of the wall.



3.10 Bonding of the Ground Cloth

3.10.1 The ground cloth, previously fabricated, was bonded to the inner portion of the sod cloth overlapping it by 2".

3.10.2 Additional reinforcement of the ground cloth bond is obtained with the use of a 5" wide crotch tape which overlaps the ground cloth joint into a double-lap shear type bond. The crotch tape also reinforces joint of the sod cloth to the section's inner wall surface.

3.11 Installation of the Manifold

3.11.1 The manifold, which was used, was of the same identical design and size as that used on the standard MUST Shelter. Its installation was the same using the standard Neoprene adapter and check valves.

3.12 Inflation of the Coated Section

3.12.1 With the inflation manifold in place, the section was inflated. We did not encounter rotation of the bladders within the cells. However, we did experience some surface wrinkling which proved to be hard to remove. The wrinkles which did occur were due to uneven distribution of the bladder length within the cells. When wrinkles occurred in certain areas, usually on top of the section, it meant that there was not sufficient bladder length to provide an endwise tension to pull the wrinkles out. We were not able to remove all of the wrinkles in each section because accessibility to the bladders was difficult, due to the friction between the inner section surface and the bladder material. By deflating and reinflation of the bladders we obtained better distribution of the bladder length within the cells. Some wrinkles disappeared and others were worked out by hand by dispersing them over a larger area. However, not all wrinkles could be removed. Zinc stearate dust was blown inside the cells, but this did not appreciably reduce the inner walls friction and allowed the bladders to slide within the cells as anticipated. The best method found to distribute the bladder's length within the cell was with the use of a 16-foot-long wooden pole. The pole was placed in the center between the ground cloth and the deflated section. By lifting the pole, the suspended section and the bladders equalized in length. The section was now inflated. The decreased friction (the bladders' surfaces were not entirely in contact with the section walls) allowed sliding of the bladder within the section cells. With this method of inflation, we obtained almost wrinkle-free outer and inner surfaces on the inflated section. Once the bladders were properly located, deflation and reinflation did not appreciably change the bladder position.

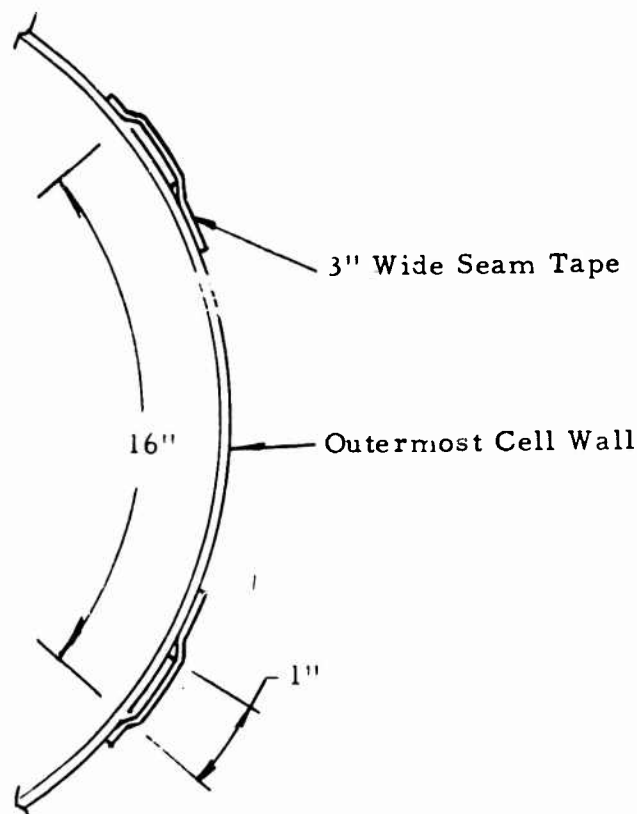
3.13

Section Tab's Removal

3.13.1

Two of the four tabs woven in during the weaving as an extension of the section walls were used to help support the inflated arch during the coating operations. The two tabs at the top were used to suspend the woven fabric arch section in horizontal position. (See Figure No. 30). These tabs were 16" apart (width of the webs) and 4" high.

Originally, we expected to use the two inner tabs as part of end closure to which the end panel slide fasteners flap could be sewn and bonded. Further study proved this consideration impractical due to the number of design changes required on the end panel attachment to make it work. The end panel could have been redesigned, but we felt it was better to adhere to the original design. Therefore, the tabs were cut off 1" long and bonded to the wall surfaces. A 3"-wide coated fabric tape was bonded over the tabs to improve the appearance and to prevent delamination. See sketch below.



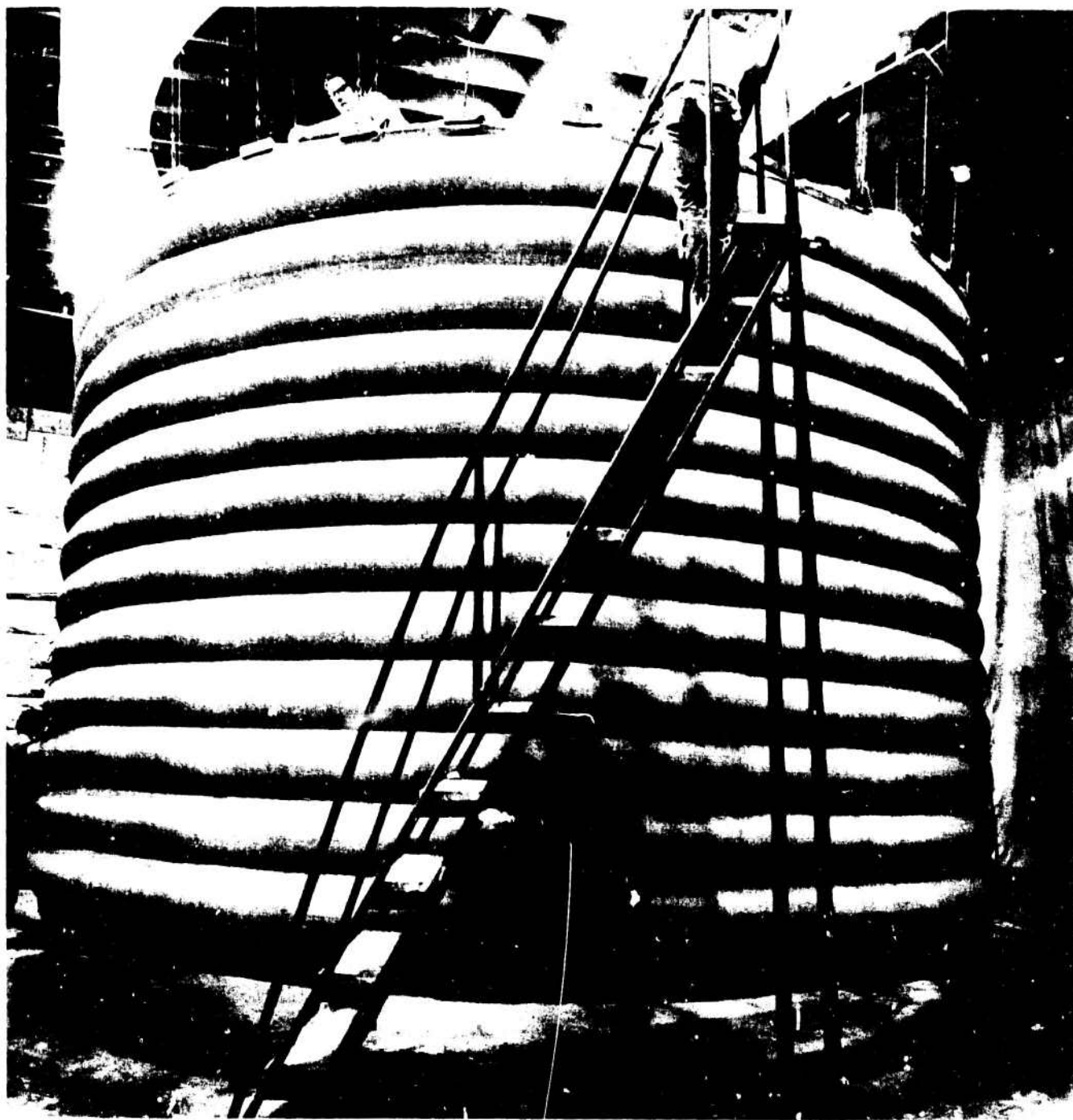


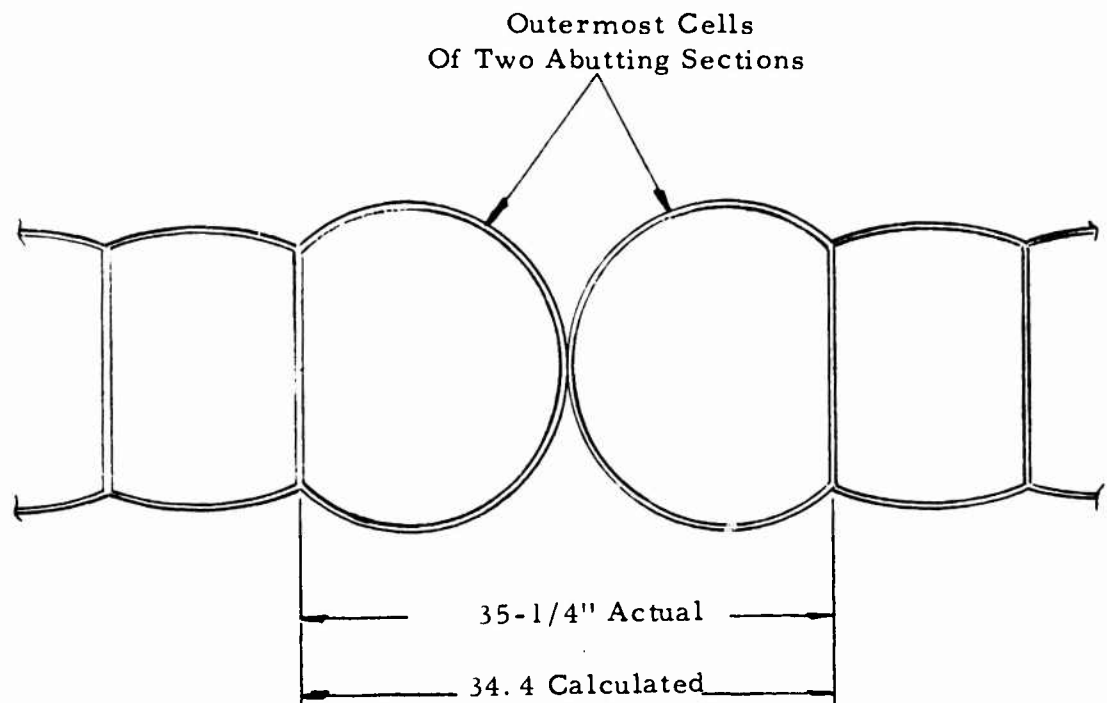
FIGURE 30: ADJUSTMENT OF THE INFLATABLE WOVEN SECTION VERTICAL
HEIGHT USING THE TABS AND SUSPENDED WOODEN CLAMPS

3.14 Bonding of Sectionalizing Straps

- 3.14.1 In production, the sectionalizing straps would have been bonded to the arch surface at the same time as the other patches and hardware. That is, after the spraying operation is completed and the section is still in the spray support stands.

However, since we did not know the exact behavior of the sections in an unrestrained condition, we decided to bond these straps in place at a later time.

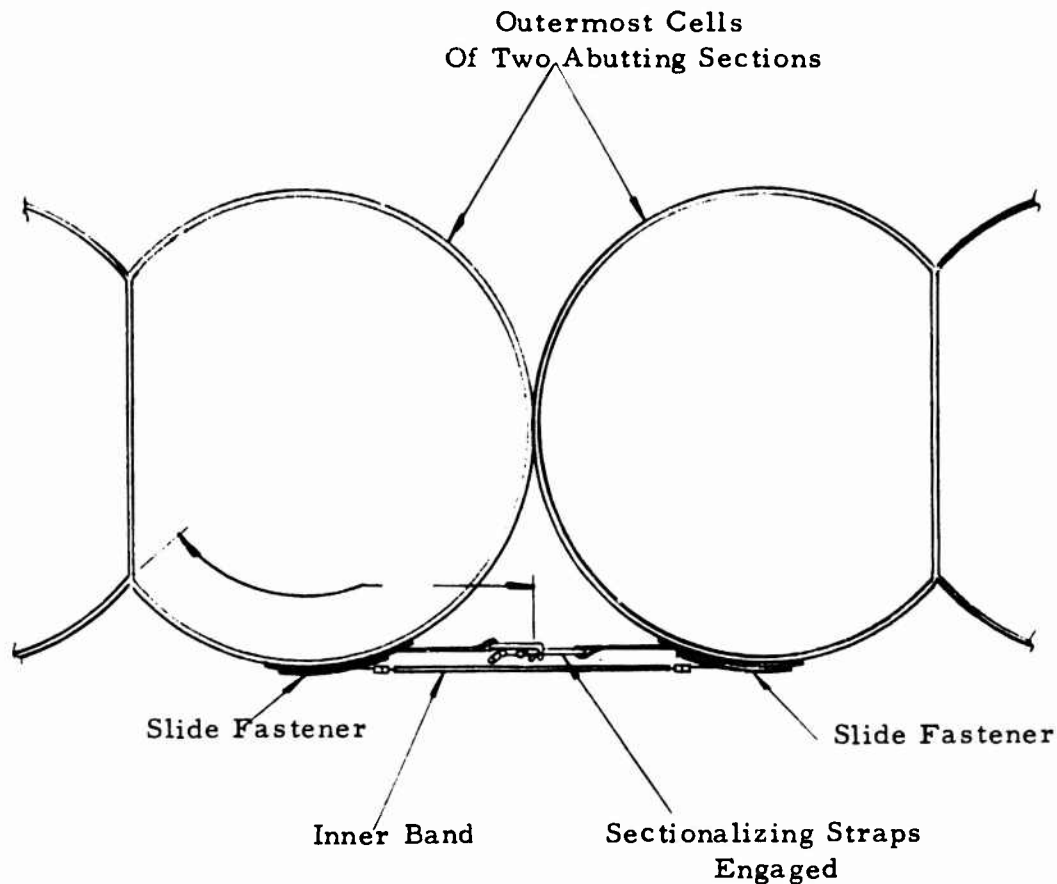
- 3.14.2 To accomplish this operation, the two partially completed sections were inflated to 1-1/2 psi air pressure and placed side by side. The distance between the webs of the two abutting sections was measured and compared with the calculated dimensions. The measured dimensions was larger by 7/8". This increase of 7/8" can be attributed to the growth due to inflation pressure and to the slight difference in diameter of two outermost cells from drawing requirements.



The distance between these webs was an important dimension since the locations of the sectionalizing straps, end panel zippers, inner bands, and outer weather strips were all measured from these webs. The webs were the base line from which all above dimensions were measured.

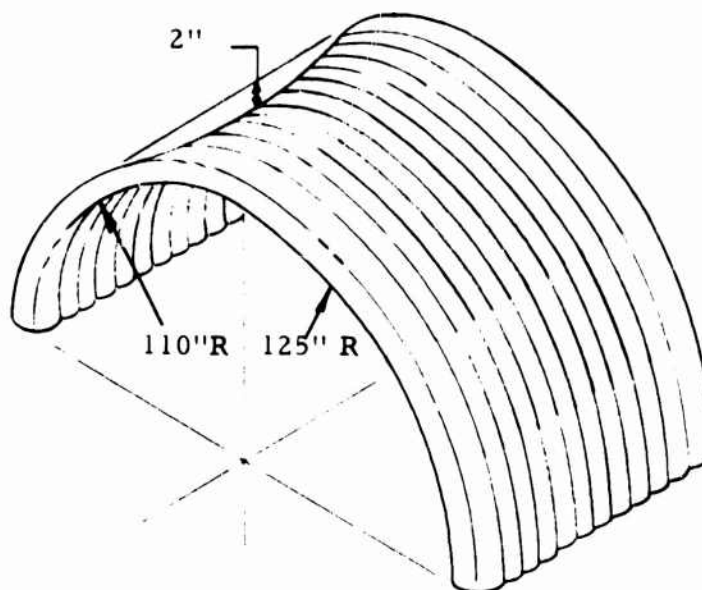
3.14.3

Because the outermost cells of the woven arch fabric were larger than the inbetween section cells, the location of the slide fastener on these cells had to be changed in relation to the web base line. This new location had to correspond to the diameter of the mating half of the separating type slide fastener located on the end panels. This change caused a relocation of the straps and their length being shortened. The straps were bonded to the wall section underneath the slide fastener. The straps' length, which has not been shortened, would (under load) cause delamination of the zipper base strips from the section wall. See sketch below.



3.14.4

The radial location of the straps was measured from the section center-line on each of the three sections. Unit No. 1, which was distorted, (discussed under Paragraph 3.3.12) had an arc radius which varied from 110 to 125 inches (versus a nominal 122"). Its outer surface was concave as shown in the sketch below.



This discrepancy was even more evident when the second section was abutted against the first. The sectionalizing straps improved this condition somewhat by pulling inward in the area where the radius was smaller and pulling outward where the section radius was larger than nominal. This condition caused some misalignment of the abutting straps of the two sections which under normal conditions would lie in the same plane parallel to the section axis.

3.15

Preparation and Bonding of Closure Wedge to End Cells

3.15.1

The fabrication of these closure units did not present any particular problem. They were completed and bonded to the section end cells using the materials and bonding procedure described in the specification for this assembly. The B.F. Goodrich Drawing 4X2125 shows the dimensional changes made to this assembly to obtain a proper fit. (Figure No. 31 shows the wedge closure to end cells.)

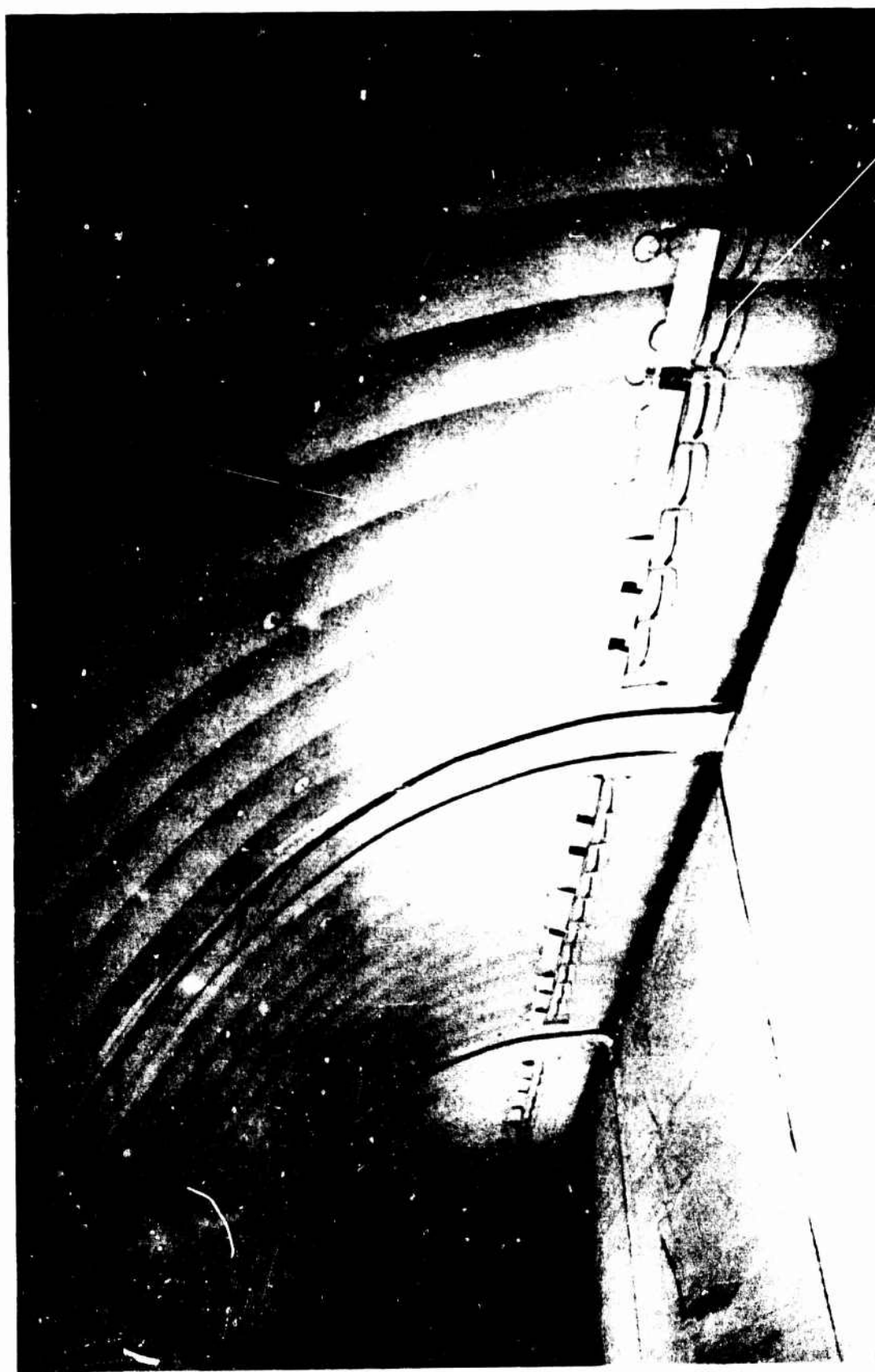
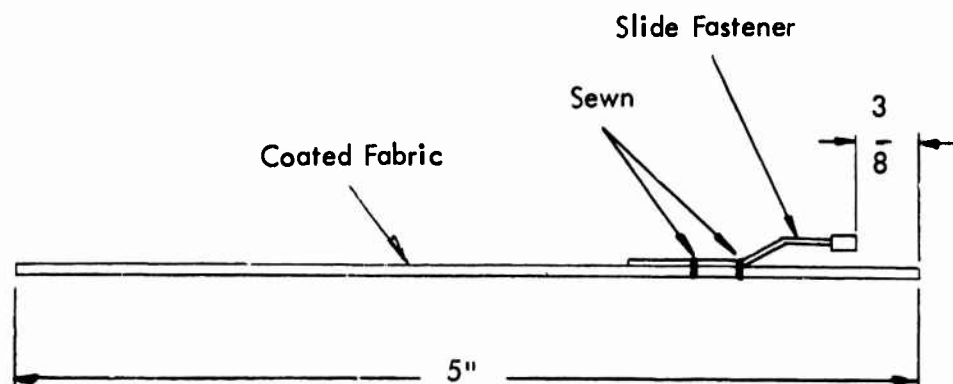


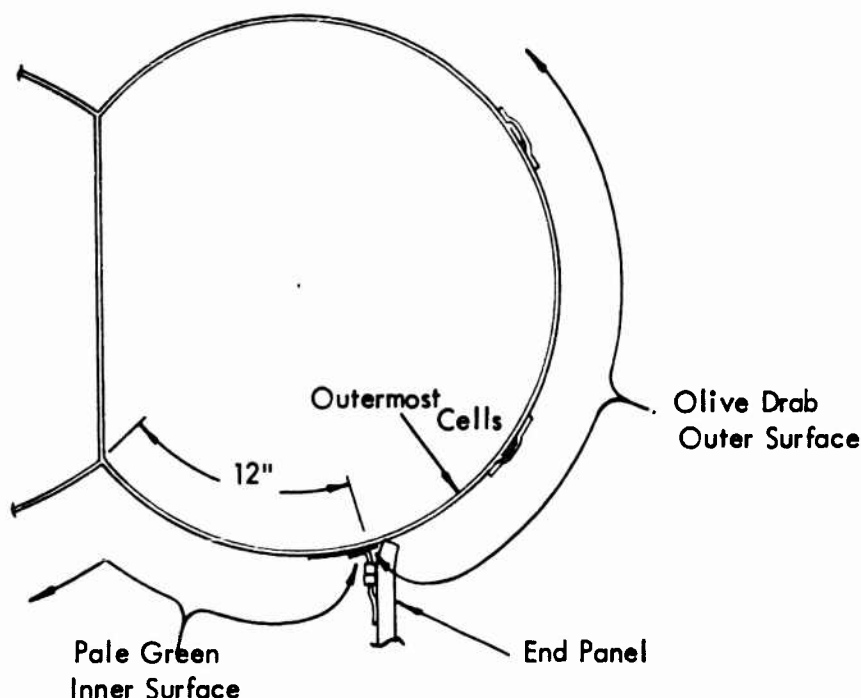
FIGURE 31: INTERIOR OF THE ASSEMBLED MUST SHELTER UNIT
CABLE SUPPORT AND BLADDER ZIPPER DETAILS

3.16 Preparation and Bonding of Separating Type Slide Fasteners

- 3.16.1 The specification calls for a separating slide fastener 31 feet $8'' + 4''$ long, containing 2347 scoops per side or 75 scoops per foot. Because of small required quantities (only 6 pcs.), we were unable to obtain the exact length of fasteners with the exact number of scoops per foot. After rejecting the first shipment, the second was not much better. We agreed to use 6 separating type slide fasteners of different lengths which ranged from 30 ft 10" to 31 ft 4".
- 3.16.2 Under normal conditions, when quantity of separating type slide fasteners are ordered which are interchangeable, a master slide fastener is provided. This fastener is permanently marked every foot, containing the same amount of scoops per foot throughout its length. By removing the pin side half of the master slide fastener, the socket side with the slider of the master slide fastener is obtained. To this master slide fastener (socket side) all pin side halves of other fasteners are assembled and marked. In that way, the interchangeability is assured.
- 3.16.3 The pin side of the slide fastener was sewn to the 5"-wide coated fabric previously marked. The alignment markings on the fabric corresponded with the marking on the slide fastener.
- 3.16.4 Due to the fact that not all fasteners were of the same length, the pin side of each of the fasteners was started at the same height ($2\frac{1}{2}''$) above the ground cloth. In that way, the zipper starting position was assured, and it corresponded to the socket side height of the end panels. The sketch below shows the cross section of the fastener sewn into the coated fabric.



- 3.16.5 The section was inflated to 1-1/2 psi air pressure and the slide fastener location marked on the two outermost cells.
- 3.16.6 The fastener assembly was then bonded to the end tube at the proper location by superimposing the one-foot alignment marks on the fastener assembly to the one-foot marks previously marked on the end cells.
- 3.16.7 The location of the slide fastener (12" from the inner surface web) exposed the inner surface color (pale green) when the end panel was assembled to it. Therefore, the surface was recoated olive drab, to correspond to the outside surface color. (See Sketch)



3.17 Bonding of Closures - Wedge to Sod Cloth

- 3.17.1 These parts, four per each section, were previously fabricated and bonded to the arch section and to the sod cloth using our standard bonding procedure. They required some fitting to obtain a proper fit. B.F. Goodrich Drawing No. 4X2124 shows the dimensional changes which were made.

- 3.18 Weather Seal Assembly. BFG Drawing No. 5X2112.
- 3.19 Inside Band Assembly. BFG Drawing No. 4X2119.
- 3.20 Floor Assembly. BFG Drawing No. 4X2118.
- 3.21 Floor transition Assembly. BFG Drawing No. 3X1742.
- 3.22 Plenum Assembly. BFG Drawing No. 5X2111.

All the above drawings detail the items that form the Inflatable MUST shelter final assembly. Since they are not an integral part or permanently attached to the MUST unit sections, they were not considered part of the development effort conducted under this program. Their fabrication was made based on the requirements of specification LP/P. Des. 42-70 and the corresponding U.S. Army Natick Laboratories drawings.

Dimensionally, the parts were changed in some areas to fit the woven fabric arch sections as shown on the corresponding B.F. Goodrich drawings. One exception to the above was the floor assembly. The three parts which constitute this assembly were fabricated per U.S. Army Natick Laboratories drawings 5 - 4 - 1410 prior to receiving the woven structure and, therefore, were shorter on each side than shown in the new B.F. Goodrich Drawing 4X2118. This discrepancy was corrected by the addition of one 12"-wide extension which was added to the floor section to obtain the proper overall floor length.

3.23 End Panels

- 3.23.1 The two end panels were fabricated according to U.S. Army Natick Laboratories requirement as stated in specification LP/P. Des. 42-70 and Drawing No. 5 - 4 1373. (End panel assembly).

As previously mentioned, the end sections were fabricated prior to completion of our adhesion tests and, therefore, were bonded using Stanley Chem. Co. Adhesive N-136 B & A.

The comparison of room temperature test results indicated that the Stanley adhesive N-136-B & A adhesive was as good as the Bostic 1039 adhesive produced by the USM Co. Since our Grantsville production personnel had a great deal of experience using the Stanley adhesive on other products such as boats, rafts, and other inflatable items, which in use are exposed to similar environmental conditions as the

MUST shelters, we decided to use this adhesive for the fabrication of the MUST shelter. On May 21, 1975, when the use of Stanley Adhesive N-136 B & A was discontinued and replaced with Bostic 1039 and Boscodur #5, the end panel fabrication was already completed. We switched to this adhesive as it provides better physical properties at elevated temperature of 200°F than the Stanley Adhesive N-136 B & A. (Figure 32 shows fabrication of the end panels.)

4.0 QUALITY CONTROL AND DIMENSIONAL INSPECTION

4.1 Material Inspection

Throughout the "MUST" unit fabrication, a high level of quality control inspection was maintained on all materials, adhesive and hardware items. Particular attention was given to the quality of workmanship. Personnel with the proper experience were assigned to this specific job and kept on that job until completed. The complete details of our Quality Assurance Program is detailed in the "Evaluation Report" document which is supplied as part of this contract.

4.2 Dimensional Inspection

4.2.1 The target dimensions for the 3-D woven fabric used for the double-wall inflatable structure was the same as for the standard MUST shelter sections.

These woven dimensions are shown in Table No. 1. They represent the average dimensions of the uninflated fabric as fabricated by Woven Structure, Co.

The dimensions of the woven arch sections when coated and assembled into a MUST shelter did not change appreciably from the as-woven dimensions.

Table No. II gives the dimensions for each coated section as assembled and inflated with 1-1/2 psi air pressure.

NOTE: The coating of the woven fabric arch sections was not in the same order as they were woven. Part No. 3 was coated first, part No. 2 second, and Part No. 1 third.

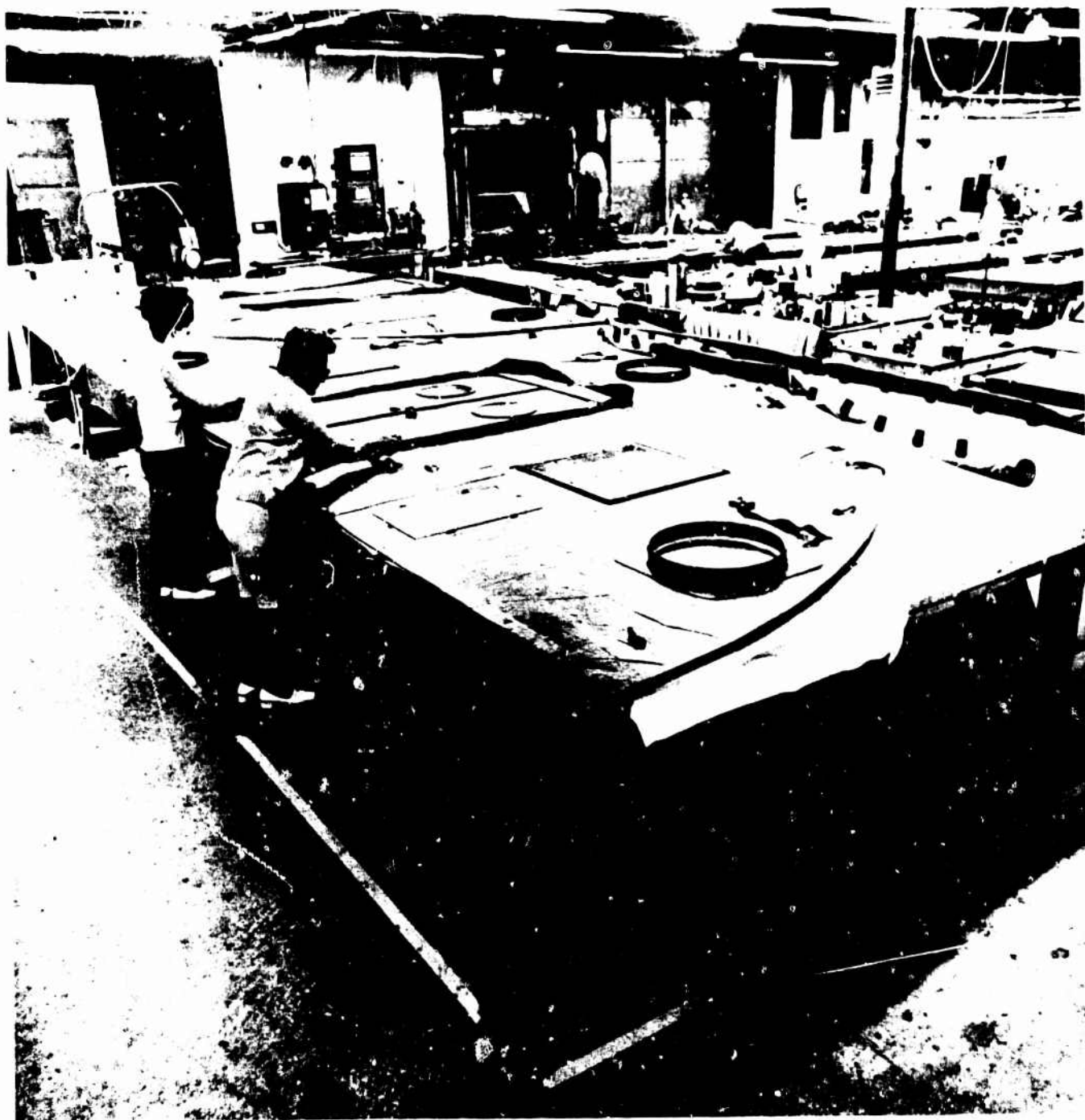


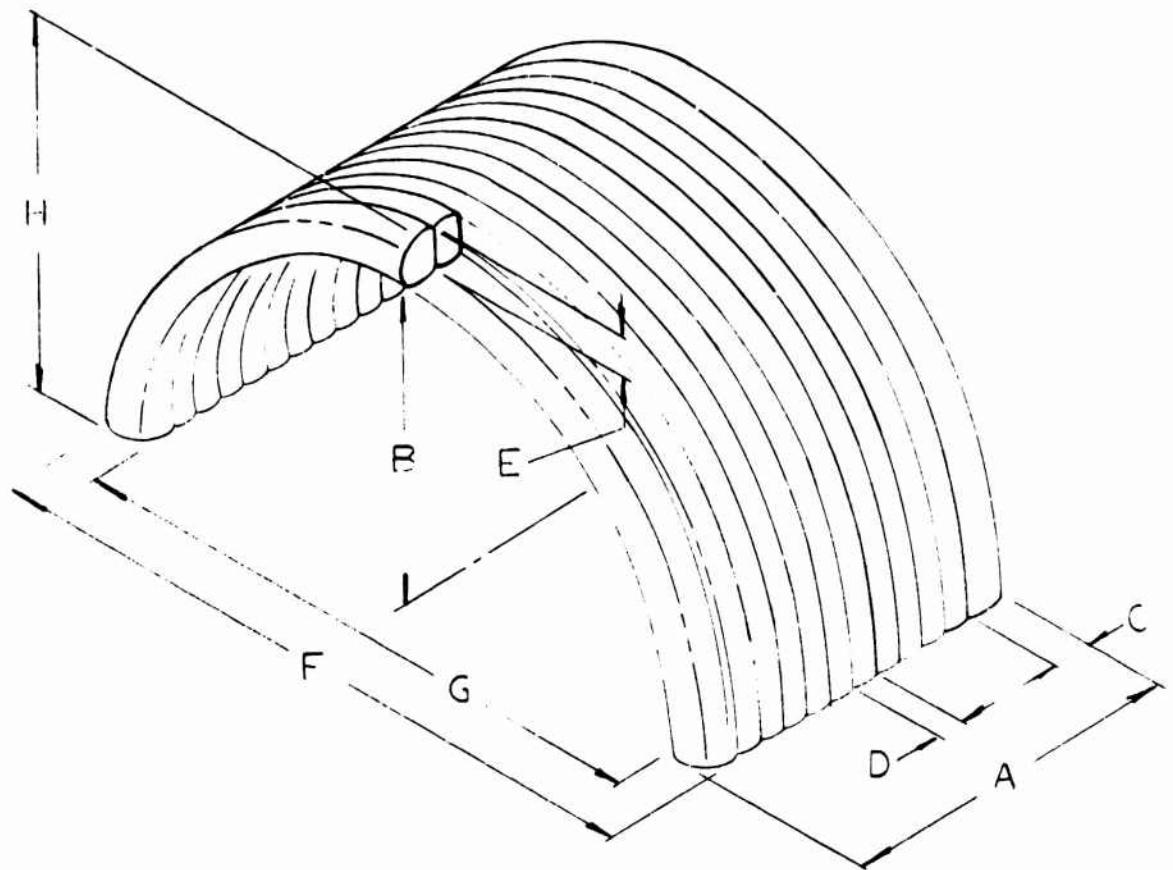
FIGURE 32: COMPLETION OF THE END PANELS

TABLE I: PHYSICAL PROPERTIES OF UNCOATED WOVEN FABRIC

	<u>Part 1</u>	<u>Part 2</u>	<u>Part 3</u>
Length of Part (measured along inner face)	39' 0"	37' 10"	38' 9"
Weight of Part	91 lb	88.5 lb	89.5 lb
Fabric Width, Not Including Tabs	162"	161"	161"
Cell Height	16"	15-3/4"	15-3/4"
Center Cell Width, Measured at Outer Face	13"	13"	13"
Center Cell Width, Measured at Inner Face	13"	13"	13"
End Cell Width, Measured at Outer Face	16"	15-3/4"	16"
End Cell Width, Measured at Inner Face	16"	15-3/4"	15-3/4"
Warp & Fill Count, Outer Face	22-1/2 x 22-1/2	22 x 22-1/2	22-1/2 x 22-1/2
Warp & Fill Count, Inner Face	23 x 27	22-1/2 x 27	22-1/2 x 27
Warp & Fill Count, Lock Area, Inner Face	45 x 53	44 x 53	42 x 53
Warp & Fill Count, Lock Area, Outer Face	44 x 44	44 x 44	44 x 44

TABLE II: DIMENSIONS OF INFLATED SECTIONS

As Woven	Part No. 1	Part No. 2	Part No. 3
As Coated	Part No. 3	Part No. 2	Part No. 1
Inflation Pressure	1.50 psi	1.50 psi	1.50 psi
Section Length Inches (A)	159.25	158.50	158
Section Height Inches (B)	121.25	120.25	120
End Cell Width (C)	17.50	17.25	17.25
Center Cell Width (Calcul.) (D)	12.42	12.40	12.35
Cell Height (As Woven) (E)	16	15.75	15.75
Section Width Outer Face (F)	281	280.50	280.50
Section Width Inner Face (G)	241	241	241
Section Outer Height End Cell (H)	142.63	141	141



4.3 Weight of the Sections and MUST Unit

- 4.3.1 The weight of each section includes the weight of the coated arch structure with all of the hardware permanently attached or bonded to it.

The twelve bladders which are contained in each cell of the arch are included in the section weight.

- 4.3.2 The weight of the individual arch assemblies of the MUST shelter with their corresponding weather seals, floors, panels, floor transitions, and end panels are shown in Table No. III which also shows a total weight for the entire assembly.

4.4 Assembly of the Three-Section MUST Shelter

- 4.4.1 Prior to final assembly of the three-section MUST shelter, each section was visually inspected for possible seam delamination, voids, cracks, pin holes, or other visible discrepancies.

- 4.4.2 The sections were then inflated at a pressure between 1-1/2 and 1-3/4 psi. After several minutes, the cell pressure leveled off at 1.5 psi which is where the pressure relief valves were set.

- 4.4.3 The sections were then placed side by side and joined together using the sectionalizing straps.

- 4.4.4 To the two outermost sections, the end panels were attached. This operation proved difficult because of the air pressure in the section. To facilitate the zipping of the end panel, the pressure in the end cells to which the zippers are bonded was decreased. With a lower pressure, the end panels could be zipped together without difficulty. With the end panel in place, the end cell pressure was returned to 1-1/2 psi.

- 4.4.5 The floor and the floor transition panels were then assembled. Also, the inner bands were installed. The plenum sections were attached to the end panels and suspended from the ceiling of each section.

The two weather panels were then placed over the section joints and strapped in place.

- 4.4.6 With these assembly operations completed, the MUST shelter unit was ready for final inspection.

TABLE III: THE WEIGHT OF THE SECTIONS

DESCRIPTION	WEIGHT PER UNIT LB.	TOTAL WEIGHT LB
Sections: No. 1 No. 2 No. 3 -	480 491.5 <u>490</u>	
Total Sections		<u>1461.5</u>
End Panel: No. 1 No. 2	182 <u>184</u>	
Total End Panels		<u>366</u>
Weather Strip 2 each required	20	40
Floor Transition 2 each required	9	18
Floor Panel 3 each required	80	240
Plenum 3 each required	7	21
Cloth Container 3 each required	13	<u>39</u>
Total Weight		2185.5

4.5 Inspection by the U. S. Army Natick Laboratories Personnel

- 4.5.1 On July 23rd and 24th, Messrs. D. Shaw and S. Shurtleff visited the B. F. Goodrich Company Plant in Grantsville, West Virginia, and visually inspected the inflated and assembled MUST shelter unit.

In the air retention test of the assembled shelter, the inflation pressure of 1.5 psi decreased to 1.2 psi after a 24-hour period which is within the acceptance requirements of the contract. It is specified in the contract that the unit be overpressurized to $2-1/4 \pm 1/4$ psi for 1/2 hour. However, during the fabrication, the sections were inflated to 2 psi for several hours without any visible damage to the section, and it was agreed not to conduct this test since special springs are required for the pressure relief valve.

- 4.5.2 Figure No. 33 shows the interior view of the assembled MUST unit with the end panel.

Figure Nos. 34 and 35 show the exterior left and right view of the MUST unit with the weather seals in place.

Upon visual acceptance by the U. S. Army Natick Laboratories' personnel, the MUST unit was disassembled, labeled, packaged, and shipped on July 25, 1975.

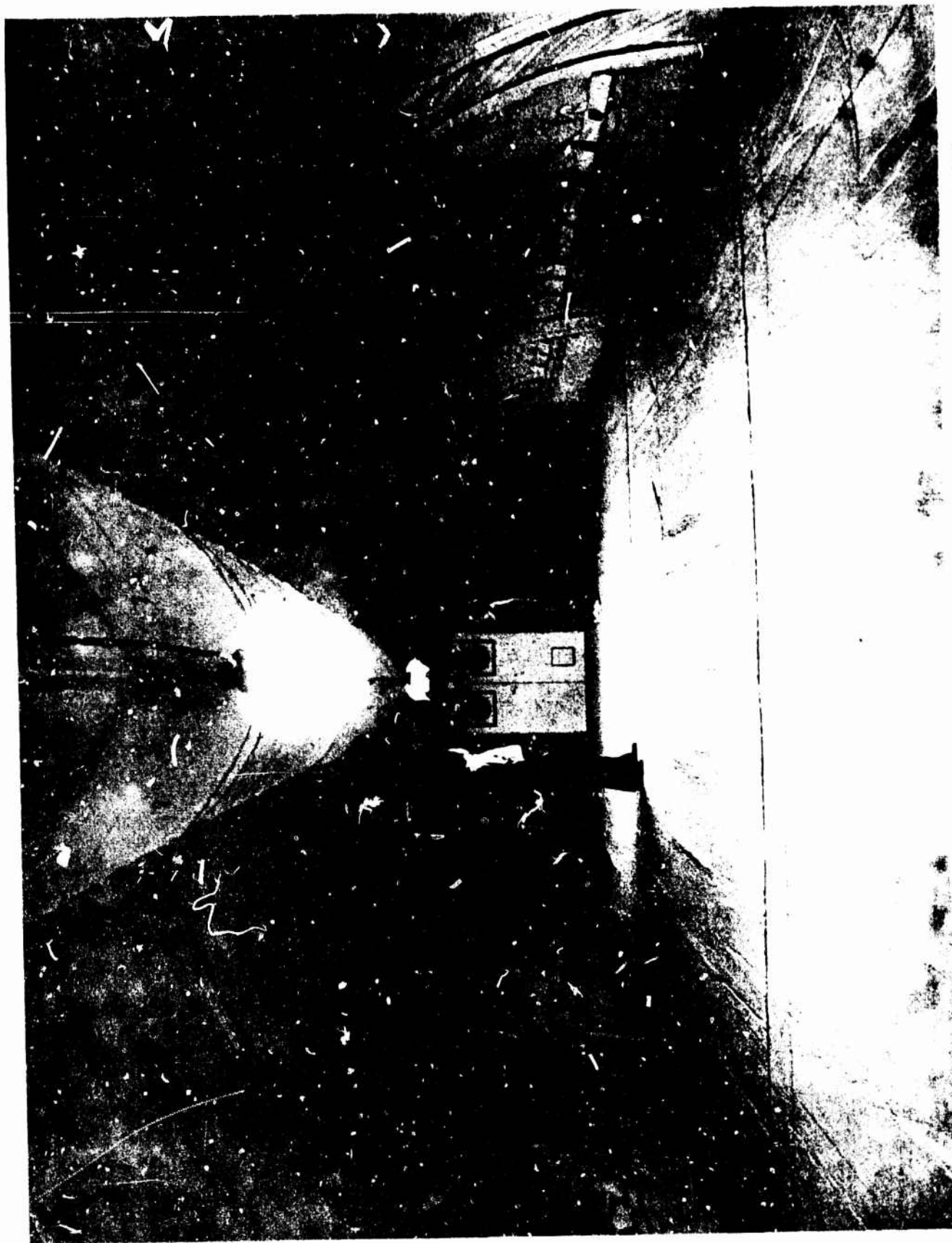


FIGURE 13: INTERIOR OF THE ASSEMBLED MUST SHELTER UNIT

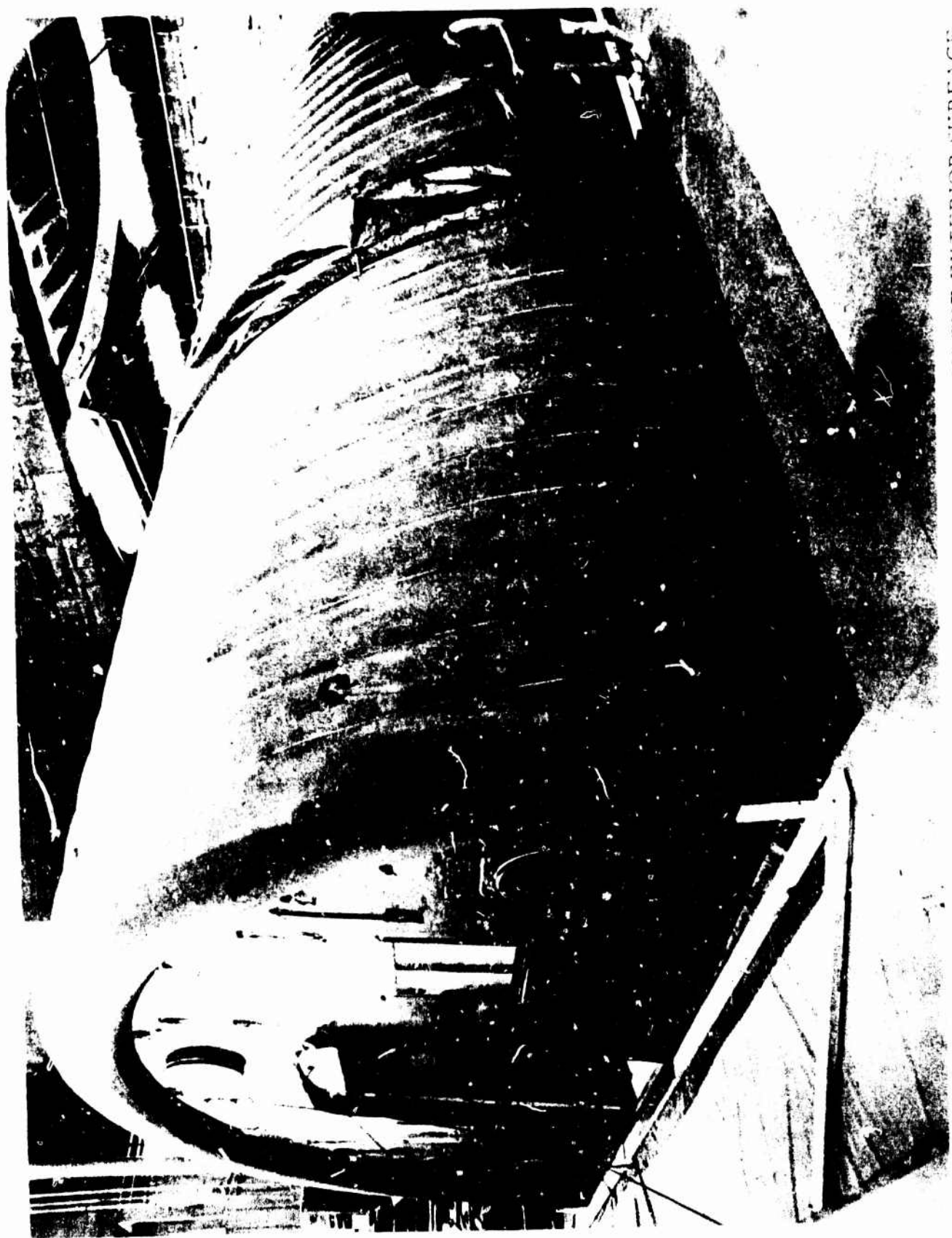


FIGURE 34: INSTALLATION OF THE WEATHER STRIPS ON THE EXTERIOR SURFACE

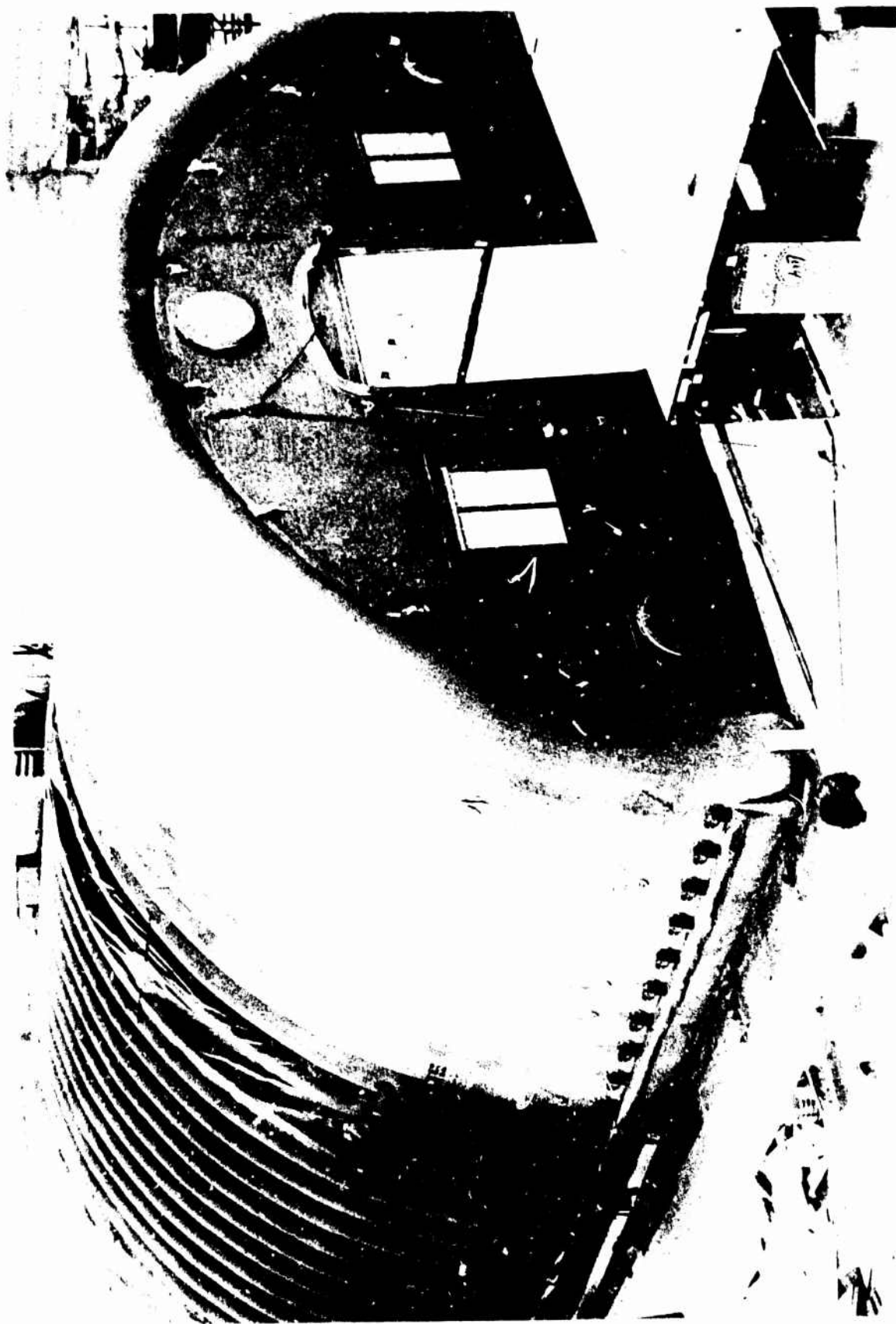


FIGURE 35: EXTERIOR OF THE MUST SHELTER UNIT - MANIFOLD SIDE

5.0 COMMENTS & RECOMMENDATIONS

5.1 The Objectives for this Program were:

- a. To develop weaving techniques which would enable weaving full-width, double-wall sections to the dimensions of the standard MUST shelter.
- b. To develop practical manufacturing techniques for the application of protective coatings to the woven fabric sections.

These objectives were accomplished in this program resulting in delivery of one three-section MUST shelter.

5.2 A number of problems were encountered throughout the program, because of materials and equipment used. A solution to these problems were found, and the three-section MUST shelter unit was produced which dimensionally is very close to the dimensions of the conventionally fabricated units.

5.3 The following recommendations for improvements in manufacturing methods, weaving, and tooling were made based on the experience gained during this contract. These modifications will improve quality, reliability and should reduce manufacturing costs.

5.3.1 Woven Structures Company recommends the use of a modified shuttleless loom with special draw rolls and conventional harnesses for weaving the arch fabric.

This new equipment would be far less complicated to program and would produce woven fabric with greater accuracy.

Most of the maintenance problems experienced with the machine used in this program would be eliminated.

The improved weaving equipment and techniques would yield a more uniform woven fabric with a minimum of repaired areas.

5.3.2 It is recommended drying ovens be installed for each fabric support fixture and that the spraying operation be conducted in temperature and humidity controlled room.

This will reduce the drying time between each spray operation and increase the quality of coating. The average drying time between each spray coating was two hours during the development program. It is estimated the drying time for each spray coating would be reduced to thirty minutes with the use of drying ovens. The proposed drying ovens are illustrated in Figure No. 36.

Conducting the spray coating operation in a controlled atmosphere will improve the quality of the coating because drying rates will be uniform preventing moisture retention in the coating. The adhesion will be more uniform between the fabric and coating as well as between each layer of coating applied by spraying. Uniform drying rates of spray coating will increase efficiency of manpower during the manufacturing operation also.

- 5.3.3 A cost analysis was conducted between an automated spray system and the hand spray system used in this contract for applying the Neoprene latex coating to the fabric. It was evident that if close tolerances and thickness of coating were not required due to weight limitations, there would be no significant cost advantage for the automatic spray system. The spraying operation requires two operators, and with four fabric support stands, the Neoprene latex coating can be applied as efficiently by hand spraying as with automatic spray equipment. Therefore, automatic spray equipment is not recommended for future manufacturing operations.
- 5.3.4 It is recommended sufficient fabric support stands be utilized to permit conducting all secondary bonding operations in the inflated condition. This will aid in location of auxiliary hardware as well as bonding operations and result in a reduction of fabrication time.
- 5.4 The quality and efficiency of manufacturing the shelter will improve with production experience. This would result in improved quality and lower cost per unit.

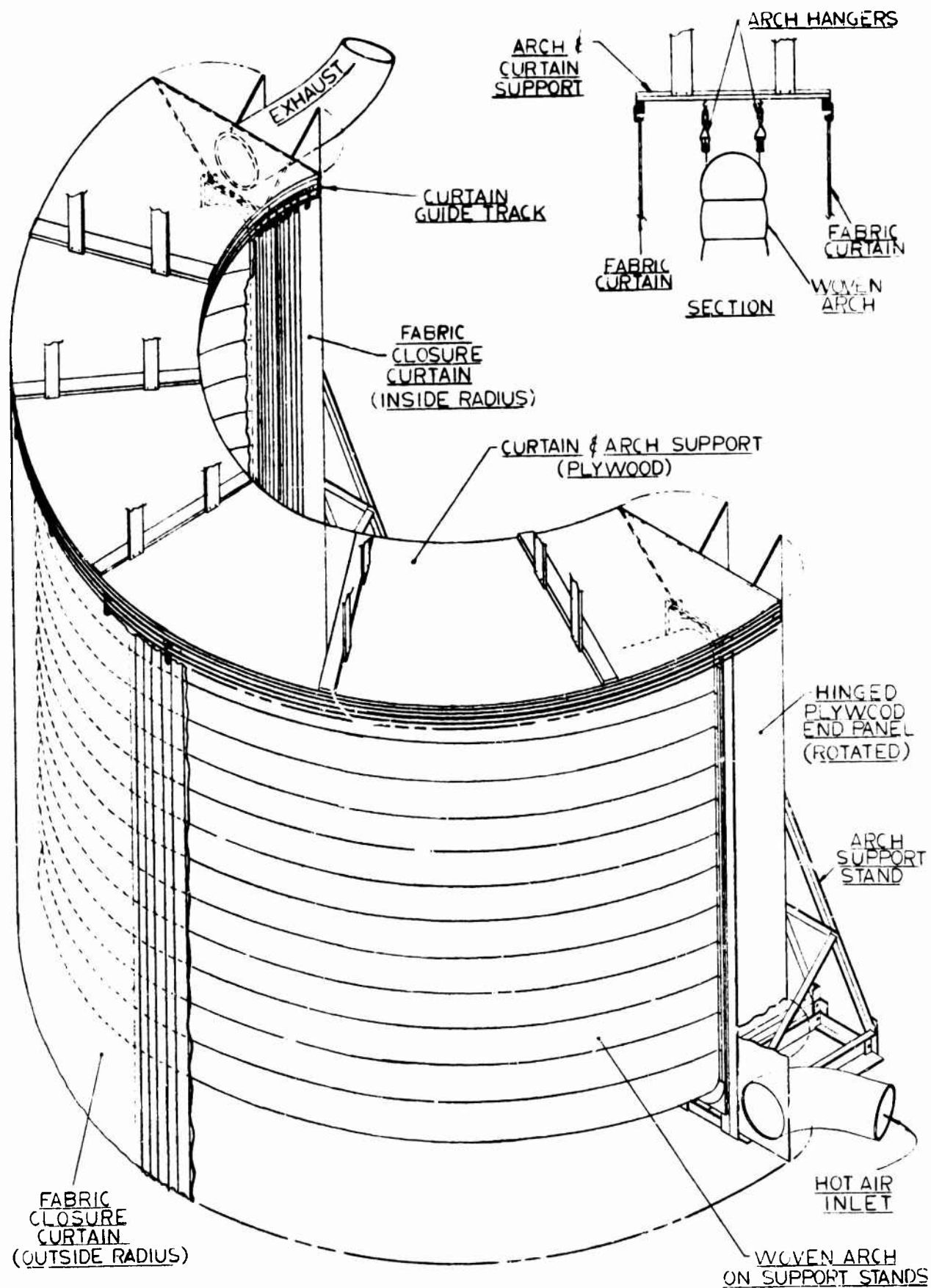


FIGURE 36: QUIK-DRY HOT AIR ENCLOSURE

6.0

MUST SHELTER - BUDGETARY COST ESTIMATE

6.1

A reliable cost estimate of a MUST shelter unit in production quantities is difficult to determine because of several unknown variables. Typical variables which could influence the cost include total quantities, delivery rate, tooling requirements, changing labor rate, cost fluctuation of materials and hardware. Since realistic values could not be assigned to these variables, it was decided to compare costs of the two manufacturing methods on a time-and-material-cost-basis for a single section. Material costs were obtained and labor costs in hours was determined for each type of construction. The hours of labor were then converted into dollar costs at a rate of \$15.00 per hour.

The cost estimate was based on the following assumptions:

1. The basic design of the MUST shelter would not change.
2. The coating materials for the 3-D woven construction would be applied by hand spraying.
3. Delivery of MUST shelters at a rate of 25 complete units per year.
4. The only difference between the two methods of construction would be in material costs and labor to the point of completion of fabric structure before application of hardware and patches.
5. The auxiliary hardware, end panels, flooring weather strips, inner band, and manifold would be the same for both types of construction and therefore, not listed in the materials cost and labor hours required.

The material costs and labor hours for each type of construction are listed in Table IV. The material and labor costs are both higher for the 3-D woven type construction than for the standard method. The total increase in cost per unit for the 3-D woven construction was estimated to be \$1,624.00 with the major share of the cost increase being for the fabric. This would result in an increase of approximately \$6,496.00 per complete MUST shelter. This cost increase must be balanced against quality and life of shelter to determine if the 3-D woven construction is cost-effective. If the life of the 3-D woven type shelter is one year greater than the standard unit the increase in manufacturing costs would be justified.

TABLE IV: FABRICATION COST COMPARISON OF MUST SHELTER SECTION

<u>Standard (SEWN) Section</u>			<u>3-D Woven Coated Section</u>		
	Hrs.	Dollars		Hrs.	Dollars
I. Materials:			I. Materials:		
1. Coated Cloth Outer Wall Surface Inner Wall Surface 52" Wide \$5/yard	80 1/y	400	1. Purchased 3-D Infl. Fabric from Woven Structure, Co.		1,540
2. Web Material \$4/yd. 52" Wide	52 1/y	208	2. Synthetic Ctg. of Neoprene Latex (50 gal.) Hypalon (10 gal.) Adhesive		150 84 10
3. Tape 3" Wide \$36/yd.	450 1/y	162	3. Tooling		100
4. Adhesive	4 gal.	30			
II. Labor			II. Labor		
1. Marking & Cutting of Panels	8 hrs.		1. Installation into Spray Unit (Marking, Cutting, Insertion of Bladder Adjustments)	48	
2. Marking & Sewing of Webs Joining Walls	48 hrs.		2. Spraying 8 coats of Neoprene latex 2 coats of Hypalon	32	
3. Apply Adhesive Bond Tape Over Seams	32 hrs.		3. Removal from Fixture & Marking	16	
4. Prepare Zipper & Sew into the Section	8 hrs.		4. Prep. of Bladder, Zipper, Cutting & Bonding	16	
			5. Final End Cutting, Sewing, & Tab Bonding	20	
Total	96 hrs.	800.00	Total	132 hrs.	1884
96 hrs. @ 15.00/hr. =		1440.00	132 hrs. @ 15.00/hr. =		1980
Total Cost		\$2240.00	Total Cost		\$3864

APPENDIX

INTEGRALLY WOVEN FABRIC FOR DEVELOPMENT
OF DOUBLE WALL INFLATABLE STRUCTURE

PREPARED BY:

WOVEN STRUCTURE, CO.
COMPTON, CA

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Integrally Woven Fabric for Development of
A Double Wall Infatable Structure

FINAL REPORT

Report for the Period April 1973 to January 1975

June 27, 1975

Prepared for B. F. Goodrich Co.

Contract No. 48100

Prepared by: W. T. Miller

A. R. Campman

Approved by: L. Parker

WOVEN STRUCTURES
618 W. Carob St.
Compton, California 90220

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ABSTRACT

A program was conducted by Woven Structures a division of HITCO to develop integrally woven double-wall fabric for inflatable structures. A conventional fly shuttle loom was programmed and modified to weave a twelve-celled fabric having the target dimensions of a full-scale module of the MUST shelter. The program tasks involved fabric and programming design, loom set up, weaving, inflating and inspecting. The report covers the work done on these tasks including the mechanical and technical problems encountered and their solutions. Three full-size parts suitable for coating were successfully produced. Recommendations are given for future work including proposed production facilities and costs.

INTEGRALLY WOVEN FABRIC FOR DEVELOPMENT OF DOUBLE-WALL INFLATABLE STRUCTURE

1.0 INTRODUCTION & BACKGROUND

1.1 Past History

The conventional method for manufacturing double-wall inflatable structures is a very involved operation and results in a product that is costly and one that has less than optimum reliability. By the present method, coated fabric is cut into patterns to provide for the inner and outer faces and for the webs that must join these faces. Considerable adhesive bonding and/or stitching is required to assemble these patterns into the inflatable shape, and the success of the finished product depends upon the quality of this multitude of joints. In a previous contract with the U. S. Army Natick Laboratories, Woven Structures division of HITCO successfully wove double-wall fabric with integrally woven webs. This fabric, woven in accordance with U.S. Patent 3,538,957 (see appendix), was 50 inches wide, had curved faces with 25 and 28 foot radii, and had two webs spaced approximately 23 inches apart. Lengths of these fabrics were coated by Woven Structures, and Natick Laboratories joined three adjacent lengths and fabricated the assembly into an inflatable structure module. This effort demonstrated feasibility and indicated that further work was required to develop shelters based on full-size woven fabric modular sections.

1.2 Scope of Program

Early in 1973 a program was started with the objective of demonstrating the technical and economic feasibility for making MUST shelters by the weaving of full-width fabric module sections, and by the subsequent coating and fabrication of these sections into complete units.

1.2 Scope of Program Cont'd.

Natick Laboratories contracted with Rubber Fabricators, Inc., (RFI) to serve as the prime contractor, and Woven Structures received a contract from RFI to furnish the basic fabric. The scope of work to be done by Woven Structures was to include the modification and setting up of equipment and the weaving of the fabric. As was later contracted, the scope was also to include a data package. RFI was to coat the material and fabricate into finished modules. This final report covers the work done by Woven Structures on this program from April 1973 to January 1975 and is intended to serve as the data package requirement of RFI's contract to Woven Structures.

2.0 PURCHASE ORDER REQUIREMENTS

The original purchase order, No. 48100, was received from RFI on April 6, 1973. The contract with its subsequent amendments had the following basic requirements:

- 2.1 Woven Structures was to furnish fabric lengths for four section modules as per the target dimensions in Figure 1. Each fabric length was to be 40 feet long measured along a nominal median radius of 130 inches. (The quantity was subsequently reduced to three fabric lengths).
- 2.2 Woven Structures was to furnish two partial fabric lengths similar to the above except that each was to be 5 yards long. (This quantity was subsequently reduced to one.) These partial lengths were to be furnished prior to the four full-length sections with one of the partial lengths to be coated by RFI for submission to Natick along with one uncoated 5-yard length.

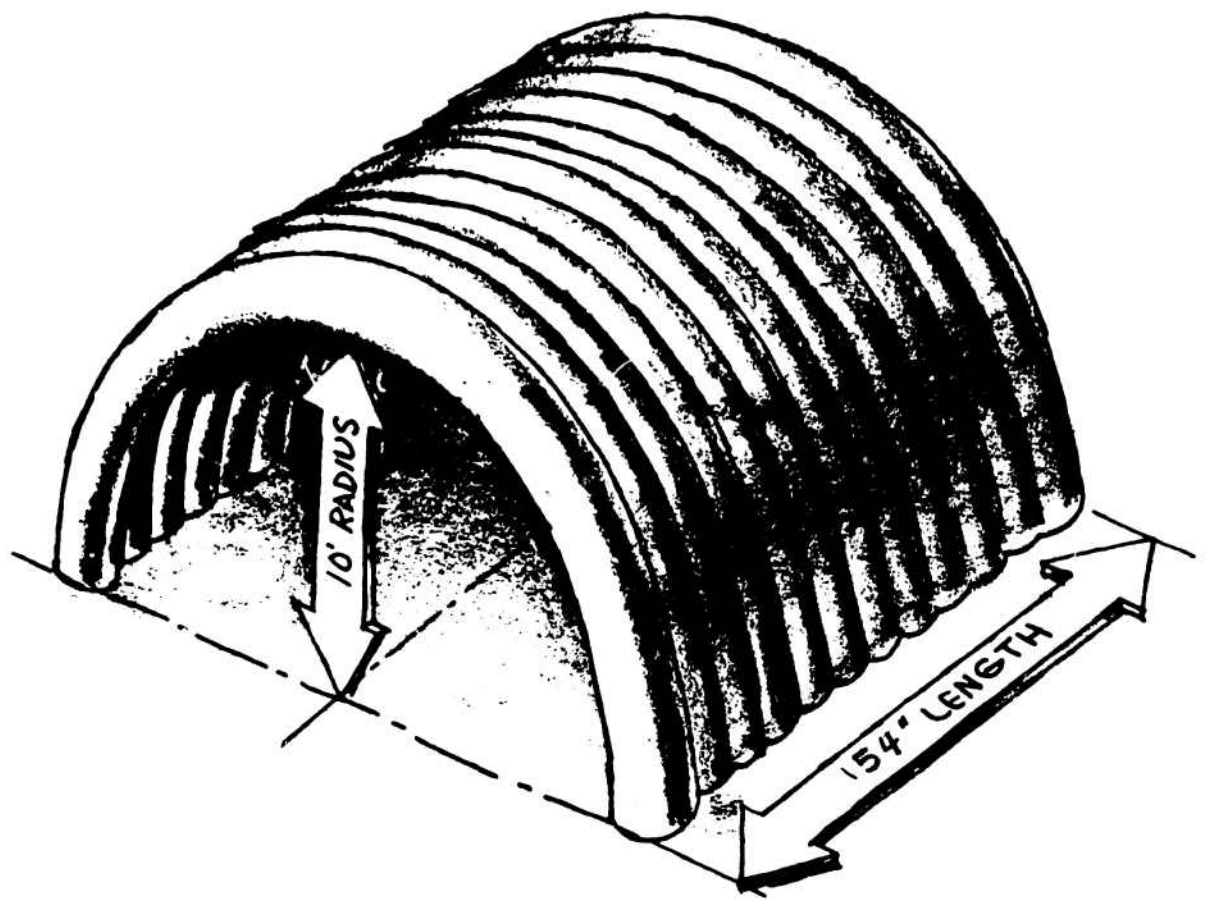


Figure 1. Contractual Target Dimensional Requirements

2.3 Heat-shrunk 840 denier polyester yarns treated with RFL-P18 predip and E-200 overdip was to be used for weaving.

2.4 RFI was to furnish 12 bladders to Woven Structures to be used for inflating and dimensionally checking each module section.

3.0 ORIGINAL PROGRAM PLAN

3.1 The technique for weaving double-wall inflatable material involves the simultaneous weaving of inner and outer face fabric and of webs joining these faces, with the cells formed by the webs in the warp direction of the fabric. The original plan for producing this fabric included the following tasks: Fabric and loom programming design, yarn procurement and preparation, loom modification, loom and creel set up, start up and debugging, weaving, fabric repair, and inspection. The major effort of this plan was expected to be the loom modification.

4.0 DEVELOPMENT OF PROGRAM AND PROBLEMS ENCOUNTERED

In the course of following the above program plan, several problems were encountered, most of which contributed to slipping of the schedule and to substantial cost overruns on the fixed-price contract. A discussion of the program, the problems encountered, and their solutions follows herewith:

4.1 Fabric and Loom Programming Design

4.1.1 The fabric design dimensions were based on the attempt to attain the existing MUST shelter configuration as closely as possible. In the previous contract with Natick where narrow width inflatable fabric was woven, it was determined that a plain weave with a target warp and fill construction of 22 x 22 in the outer face was satisfactory. The treated

4.1.1 Cont'd.

840 denier Dacron yarn used with the construction provided a close enough weave in both the inner and outer fabric faces for accepting the neoprene and Hypalon coatings. From the earlier contract, a 1-1/2" width of lock was used between the webs and the face fabrics. The weave in the lock area was a basket type with the target construction of 44 x 44 in the outer face. For the new full width fabric, it was decided to use the same lock area fabric construction, but to use a 2" lock as an extra margin of safety. Also, since it was anticipated that the coating operation might again involve the attaching of the expanded fabric to a frame, extra widths of fabric faces were to be provided beyond the locks of the outermost webs to serve as tabs for anchoring to the frame. After coating, these tabs could be removed.

4.1.2 The cross section of the fabric in an expanded condition was used as a basis for design as is shown in Figure 2. It was not possible to accurately predict the exact shapes and dimensions of the intermediate and end cells after inflation, but preliminary calculations indicated that the overall width of the inflated module would be about 154", and that the distance between the faces of the intermediate cells would expand to about 20". The 10' inside radius requirement was designed into the fabric and into the programming from the estimated inflated reference surface. See Figure 3.

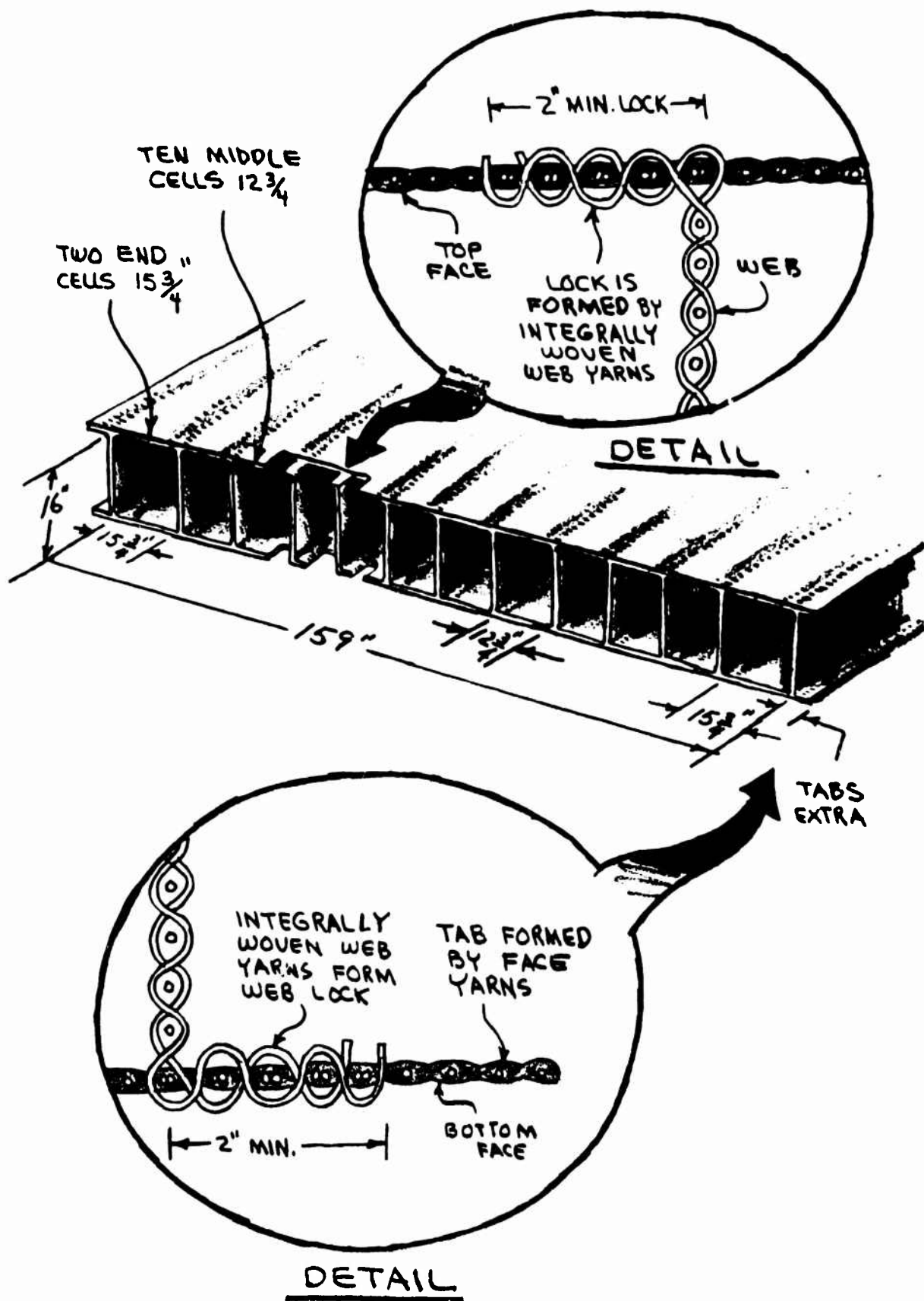


Figure 2. Cross Section Design of Inflatable Fabric in Expanded Position

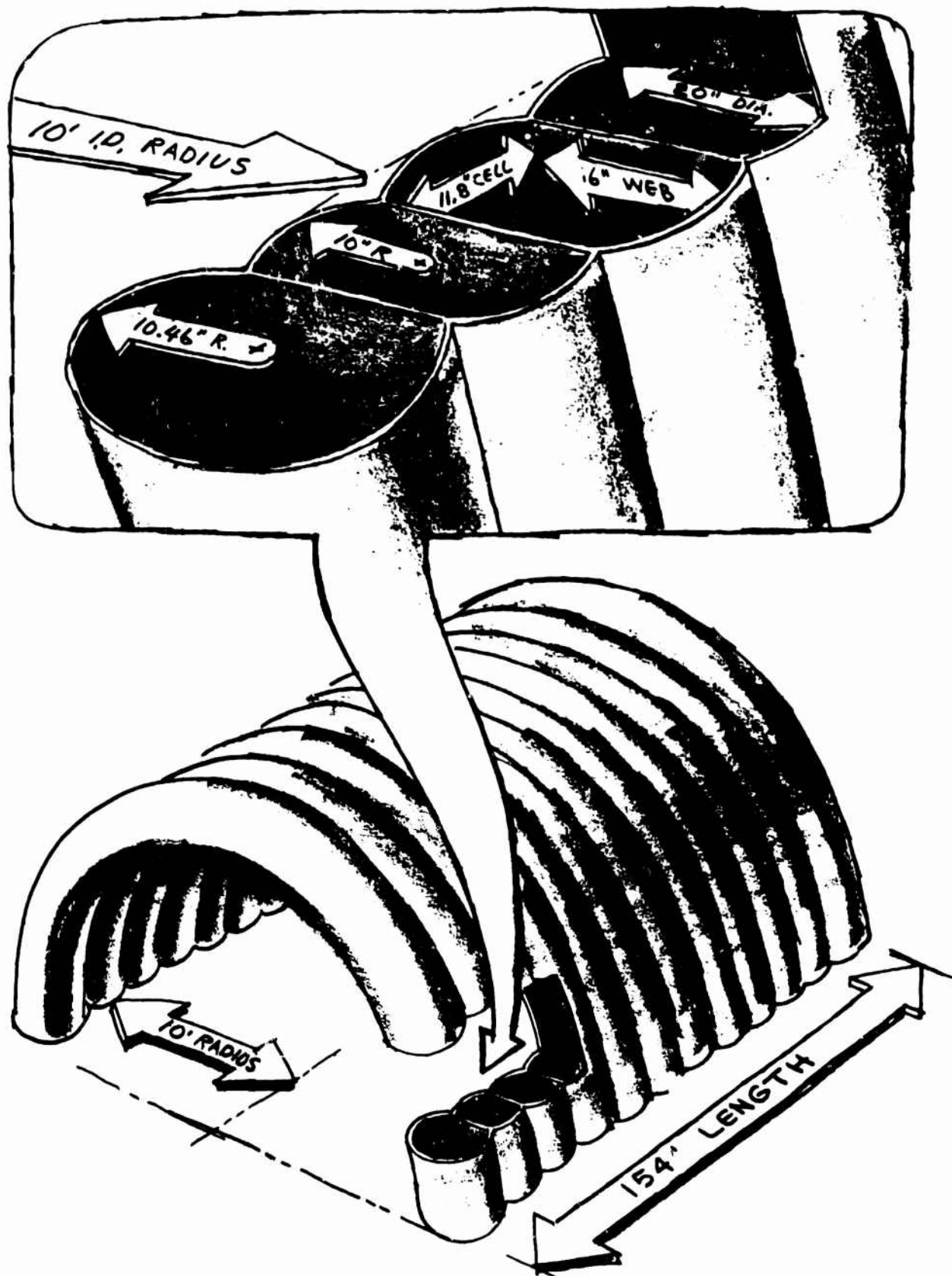


FIGURE 3. Estimated Inflated Cell Dimensions

4.1.3 Originally, consideration had been given to designing the fabric and loom programming based on using only harness type programming. Because it would have required 24 harnesses to accommodate the 2 faces, 13 webs, and 26 locks, it was found that the space occupied by the harness frames would be too large for the available loom. Even if space were available, it was felt that the depth of the harnesses might result in too small a shed opening. Approximately 12 inches between the reed cap and crankshaft would have been needed to accommodate the harness frames, but only 7 inches were available. Therefore, during the proposal effort, it was planned to use a combination of harnesses and a Jacquard program. However, after the contract effort was started, the preliminary design indicated that the planned method would introduce a large amount of floater fill yarns which would contribute nothing to the part and would add additional weight and possibly interfere with the coating operation. It was then decided to go to an all-Jacquard program and this resulted in a very long engineering design effort. This in turn increased the time and complexity of the set up because of the necessity of tying in two Jacquard heads.

4.1.4 In developing the programming for the Jacquard heads, it was first necessary to lay out master sheets essentially similar to Figures 2 and 4 and to transform the dimensions of each face, rib, lock and tab from inches to warp ends in order to determine the number of warp ends required for each such element. This determination indicated that approximately 13,000 ends of warp yarns were required, and since two 1200-

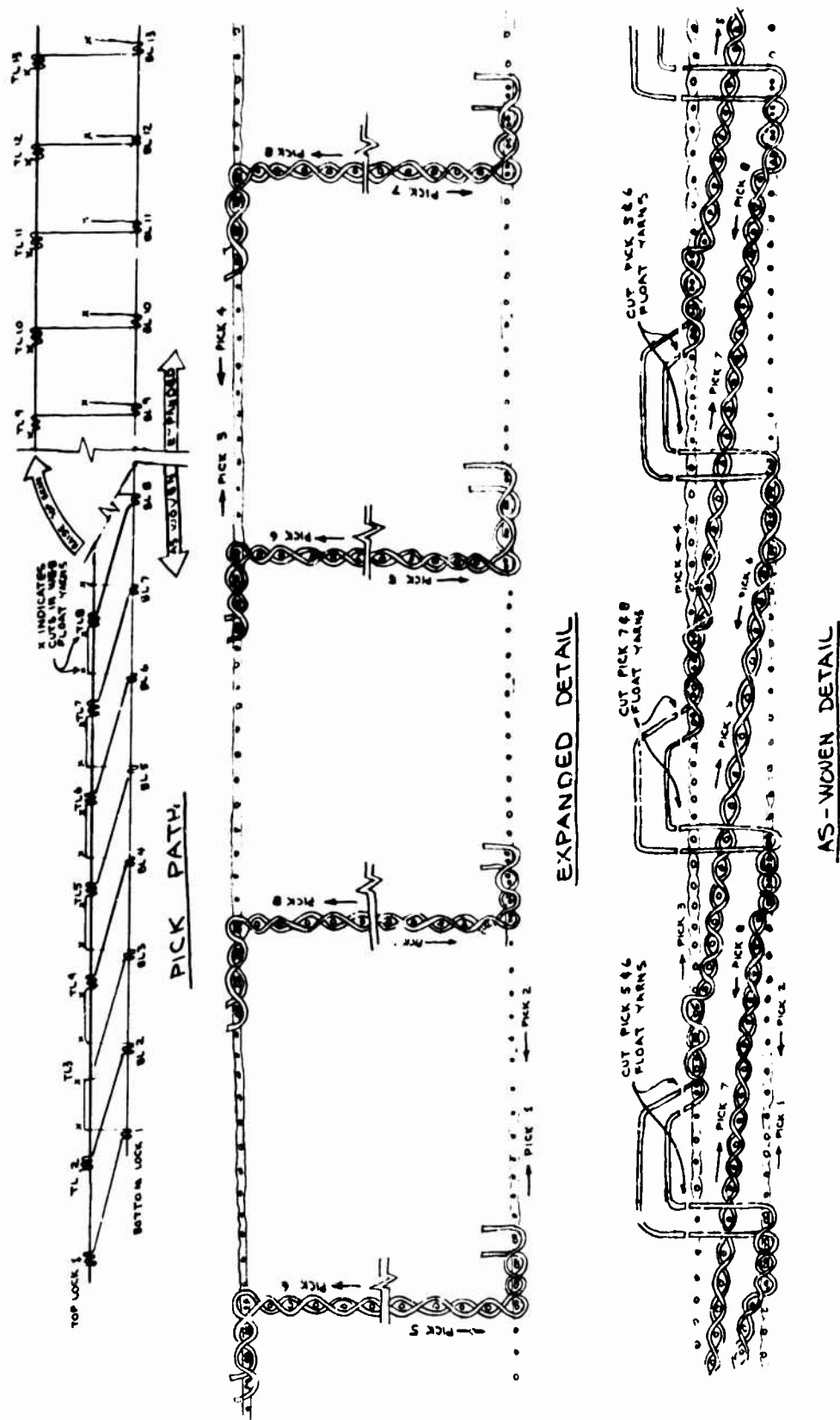


Figure 4 - Schematic Illustration of Picking Sequence

4.1.4 Cont'd.

hook Jacquard heads were to be used, it was necessary that each hook had to control the lifting of a multiple number of these warp ends. Those warp ends which could operate as a unit or group and be operated from a single hook were selected, and these groups were numbered consecutively. The path of each pick was traced through the numbered groups of warp ends and those numbered groups which were above the path of a pick were colored red on standard Jacquard design sheets. Those groups which were below the path of a pick were uncolored on the design sheet. These sheets were then converted into conventional Jacquard cards.

4.1.5 In weaving a fabric such as the multi-celled inflatable material of this effort, it is necessary, in effect, to weave four distinct fabrics, one above the other, simultaneously, and to join these fabrics by weaving them together at selected areas. Figure 4 schematically illustrates the picking sequence used in the design for this fabric. Odd numbered picks are made with the shuttle moving to the right and even numbered picks are made with the shuttle moving to the left. Picks 1 and 2 are woven through the bottom face warp with one half the bottom face warp yarn raised and all web yarns raised. Picks 3 and 4 are woven through the top face warp with alternating halves of the top face warp yarns raised. Picks 5 and 6 form odd numbered webs, that is, numbers 1, 3, 5, 7, 9, 11 and 13. Pick 5 is taken through one-half of top face lock number 1, then through the length of the first rib, then through one half the warp of bottom face lock number 1,

4.1.5 Cont'd.

then floats over a portion of the top face warp to the left edge of the top face lock and number 3 and similarly to the last cell web at the right hand side. Pick 6 follows the same path as 5 except for the alternate warp shed. Pick 7 floats under the top fabric to the top face lock number 2 where it weaves through the lock, then through web 2, then through bottom face lock number 2, then is taken above the top face warp and floats to the left edge of top face lock number 4, then through web 4 and similarly through webs 6, 8, 10 and 12. Pick 8 travels the same path except through the alternate warp shed. The float yarns shown in Figure 4 are trimmed during the weaving operation. The above, of course, represents the simplified schematic sequence accounting for 8 picks. For this program, it was necessary to prepare individual sheets depicting the position of each of the 2,400 hooks for each pick.

4.2 Yarn Procurement and Preparation

4.2.1 The specifications for the MUST program call for the use of 4-oz. polyester fabric which is woven from relatively low denier yarn. Since multi-celled, multi-lengthed, extra wide fabric cannot be heat set and treated in any known existing equipment, it was planned to use 840 denier polyester yarn which was previously heat shrunk and treated with a resorcinol formaldehyde in latex form (RFL). This denier was the smallest available with this treatment. The customer requested that the yarn treatment be switched to one using an isocyanate (P-18) predip and resorcinol formaldehyde (E-200) overdip in order to obtain better adhesion of coating to the fabric.

4.2.1 Cont'd.

Bibb Manufacturing Co., who was to supply the yarn, ran into problems trying to produce this finish primarily because of the inability to use the solvent system in their equipment. After a delay of several weeks, they were able to supply a material that substituted an aqueous P-18 predip instead of the solvent based material.

4.2.2 When this yarn was received, it appeared to have its filaments more cohesively bonded than conventional RFL-treated material used on the previous contract. This raised a concern that perhaps a 22 x 22 construction fabric might now be too open for coating. Samples of flat fabric, one having this construction and one having a more closed construction to simulate the weave of the inner face (approximately 22 x 25) were woven and submitted to the customer for coating evaluation. It was also of great concern because it was too late to change the planned warp count for the fabric since the design had progressed too far by this time. However, it was reported back from RFI that the samples were satisfactory. This special yarn treatment also made the yarn stiffer and more difficult to wind on the creel supply packages, and considerable time was expended in modifying the winders to handle this yarn.

4.3 Loom Modifications

4.3.1 The loom used for this program was a Draper Model X-2 which had been previously widened to a reed length of 192 inches. The loom had been equipped with a crankshaft for operating the lay and take-up mechanism, and with a bottom shaft which had cams to operate harness frames. The bottom shaft also provided

4.3.1 Cont'd.

the power to drive the picking mechanism. This is the conventional arrangement for looms of this type which are normally used to weave low warp count light weight fabrics. For this effort, it was necessary to modify the loom to drive two Jacquard heads, beef up the loom to handle 13,000+ warp ends, and to install draw rolls necessary to form the different lengths of face fabric.

4.3.2 In one loom revolution, four motions are involved; picking (the motion for driving the shuttle back and forth), lay (the motion that moves the reed back and forth and beats the fill yarns into the fabric), take up (the motion that advances the fabric as it is woven), and harness (the motion that raises part of the warp yarns to form a shed opening through which the shuttle passes). The motions impose loads of varying magnitudes, and two of these, picking and harness, overlap. The picking cams, cams that drive the picker sticks which in turn drive the shuttle, are mounted on the bottom shaft and impose a severe load of very short duration but of extreme magnitude because of the necessity of accelerating the shuttle from 0 to approximately 50 to 60 feet per second in a very short interval of time. The left cam is shown in Figure 5. The harness motion for the modified loom had to provide for the lifting of weights (lingoes) and heddles coming down from the Jacquard heads. This amounted to about 2,000 pounds that had to be raised approximately 7 inches in 1/3 revolution, or in 1/4 second. The take up and lay motion loads on the crankshaft were expected to be of lesser magnitude

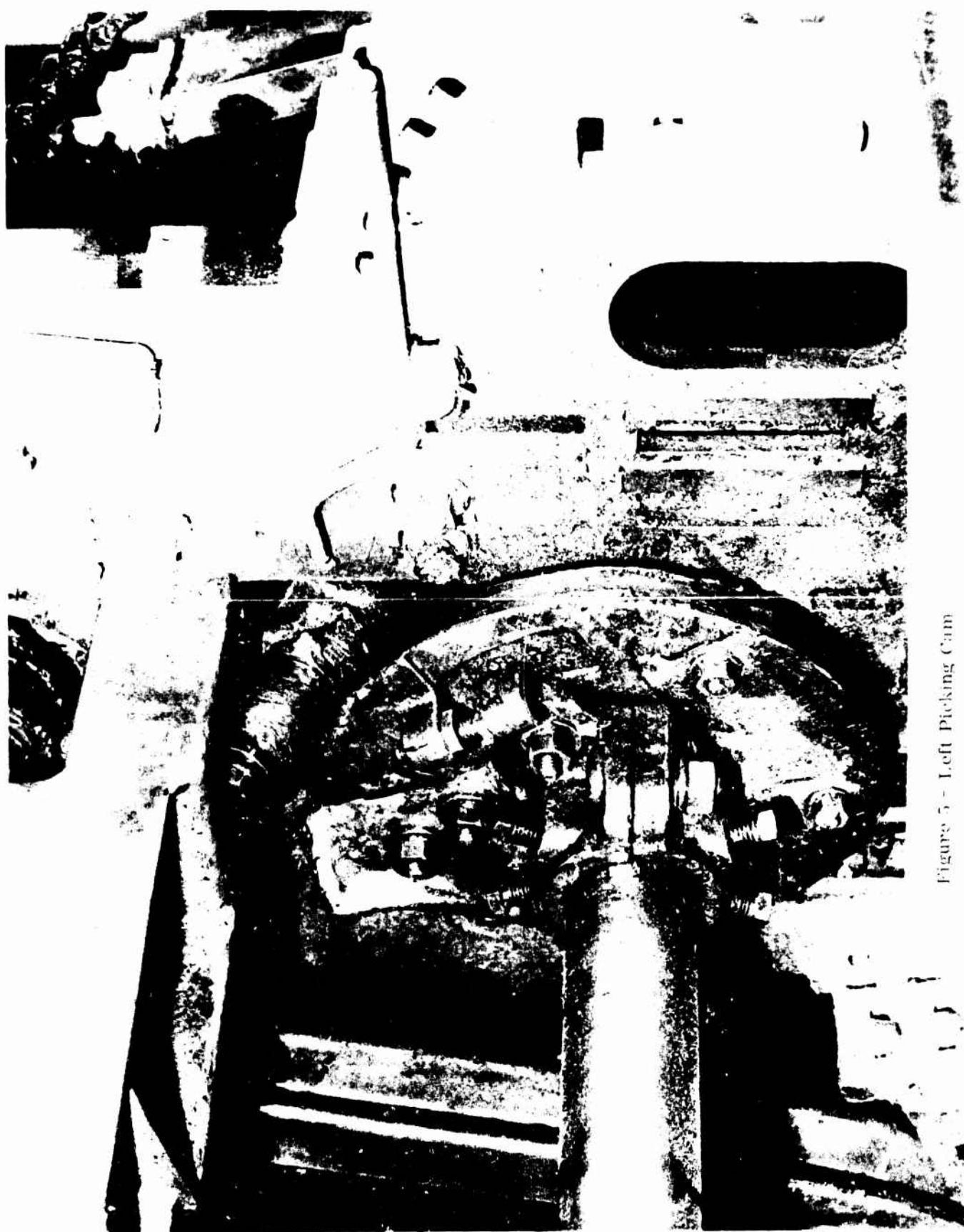


Figure 5 - Left Picking Cam

4.3.2 Cont'd.

and since they did not occur simultaneously with the picking and harness loads, were not considered of major concern.

4.3.3 The drive motor for the loom before modification was a conventional 2-horsepower textile unit incorporating a mechanical clutch and brake, and this unit was mounted on a stand attached to the right side of the loom. A motor pinion engaged a gear which was attached to the lay crank-shaft and this gear engaged a second gear which drove the bottom or picking shaft. While it was anticipated that this power source would be too small for the loads that were to be added by modification, it was not possible to predict this increased requirement. Changing the power source had to wait until the loom was completely set up and ready to operate.

4.3.4 After set up was complete and the loom was ready for its preliminary trial run, as expected, the power for the unit was found to be woefully insufficient, and no standard large size textile motor with a built in clutch and brake was available as a replacement. Preliminary calculations and amperage readings indicated that at least a 5 horsepower motor would be required. It was also determined that the bottom shaft of the loom was not large enough to handle the combined picking motion and harness motion or Jacquard load, so it was decided to add a separate shaft from a new drive unit just to handle the Jacquard load. This countershaft was located parallel to the main drive shaft and extended the full loom width. The new motor drive unit consisted of the

4.3.4 Cont'd.

5 horsepower motor, electromagnetic brake, clutch, and gear reducer. The new Jacquard drive shaft was in line with and coupled to the outlet shaft of the gear reducer. The complete drive unit was mounted on a plate, and since it occupied a space considerably larger than the original motor drive, it was necessary to floor mount the new unit at the rear of the right side of the loom. The revised power train now consisted of the following: A 5-horsepower motor-reducer unit, a loom crankshaft for driving the lay mechanism, a bottom shaft for driving the picking motion, and a countershaft for driving the Jacquard heads. This countershaft also powered the take up rolls.

4.3.5 When the loom was started with the new drive unit, it was again found to be underpowered. The pulsating loads were great enough to slow down the motor progressively until there was insufficient power for the picking motion, and the shuttle was unable to make complete traverses through the shed opening. At that point, serious consideration was given to installing a flywheel in the system to reduce the motor slowdown, but this idea was abandoned because of its potential safety hazard. Instead, it was decided to go to a larger motor. A heavy frame, 20 horsepower, 1800 RPM motor was located and was rewound to 18 horsepower, 1200 RPM. It was hoped that the large rotor on this motor would also serve as a flywheel. However, as an added feature, the rewound motor was provided with shaft extensions on both sides, one of which could later be fitted with a flywheel, if it became absolutely necessary.

- 4.3.6 When the loom was started again, severe vibrations caused the motor drive unit to break away from the concrete floor and the main loom frame appeared to be flexing excessively. To correct this, the loom was raised 6 inches above the floor, and 3 1/2 foot deep pits were dug below the loom feet and in the area under the drive unit. These pits were filled with concrete to provide sufficient anchoring weight that would exceed the vertical components of any lifting forces. Steel plates 1 1/4" thick were anchored to these concrete piers, the loom lowered and bolted to the steel plates. The loom was started and found to be adequately secured.
- 4.3.7 In order to determine the adequacy of the drive unit and to resolve the question of need for a fly wheel, a tachometer generator unit attached to the motor shaft was connected to a high speed recording chart unit capable of picking up motor speed fluctuations in enough detail to analyze the action of the motor. Chart tracings were taken of the motor speed when driving the Jacquard harness motion alone, the picking motion alone, and all motions operating together. Under the most severe conditions, the motor speed dropped 200 RPM but recovered to 1200 RPM within 3 or 4 motor revolutions, or in less than 1/4 of a loom revolution. With this rapid recovery in speed, it was no longer believed necessary to incorporate a flywheel. It was then decided that the unit was now adequately powered.
- 4.3.8 The finalized motor drive and power train consisted of the following:

4.3.8.1 Motor Drive Unit - This was made up of a 1200 RPM motor with a 22-tooth timing pulley on its shaft driving a 40-tooth timing pulley on a second shaft parallel to the motor. The motor shaft had a brake mounted outboard of its pulley. The second shaft had a electromagnetic clutch mounted in combination with its 40-tooth timing pulley, and the second shaft was coupled to the input of a 10:1 worm gear reducer.

4.3.8.2 Power Train - The right side shaft of the gear reducer was connected to the right Jacquard head above through number 80 sprockets and chain. The left side shaft of the gear reducer was equipped with a sprocket and was linked to the right end of the loom crankshaft through a number 120 drive chain in 1:1 ratio. The loom crankshaft speed was thus 66 RPM. Through gearing, the bottom shaft was driven at half speed from the crankshaft in a 1:2 gear ratio. The left shaft of the gear reducer was also coupled to the counter-shaft, which at the left end of the loom, was connected to the left Jacquard head above through number 80 sprockets and chain. The motor drive and power train are shown schematically in Figure 6. Photographs of the motor drive unit are shown in Figures 7 and 8.

4.3.9 To support the Jacquard heads over the loom, a steel gantry was erected. Because of the problem in not being able to anticipate the loads, and because of space limitations, it was necessary to reinforce the structure several times after the loom was finally started. The most serious problem was the vibration

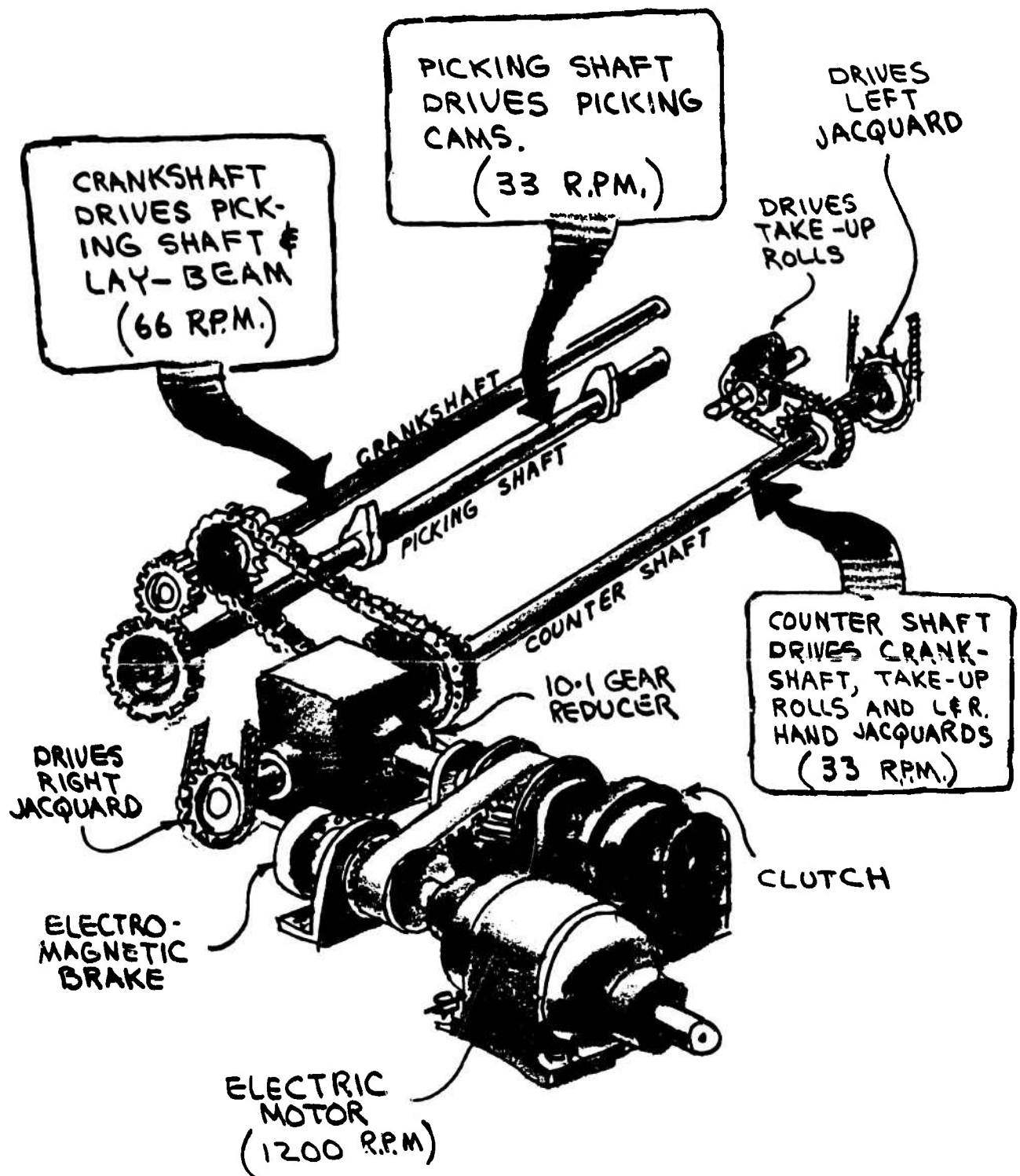
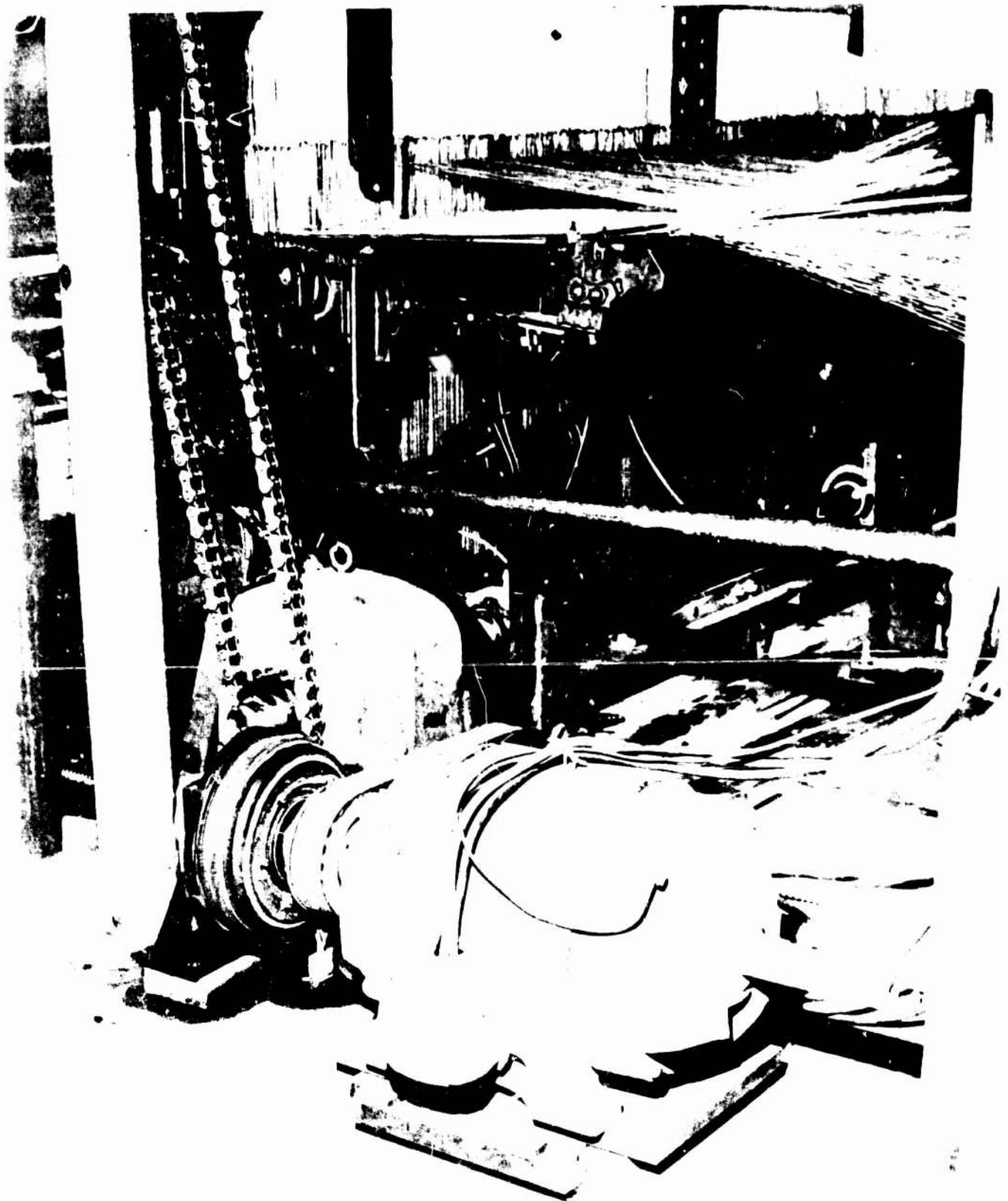


Figure 6 - Schematic View of Motor Drive and Power Train



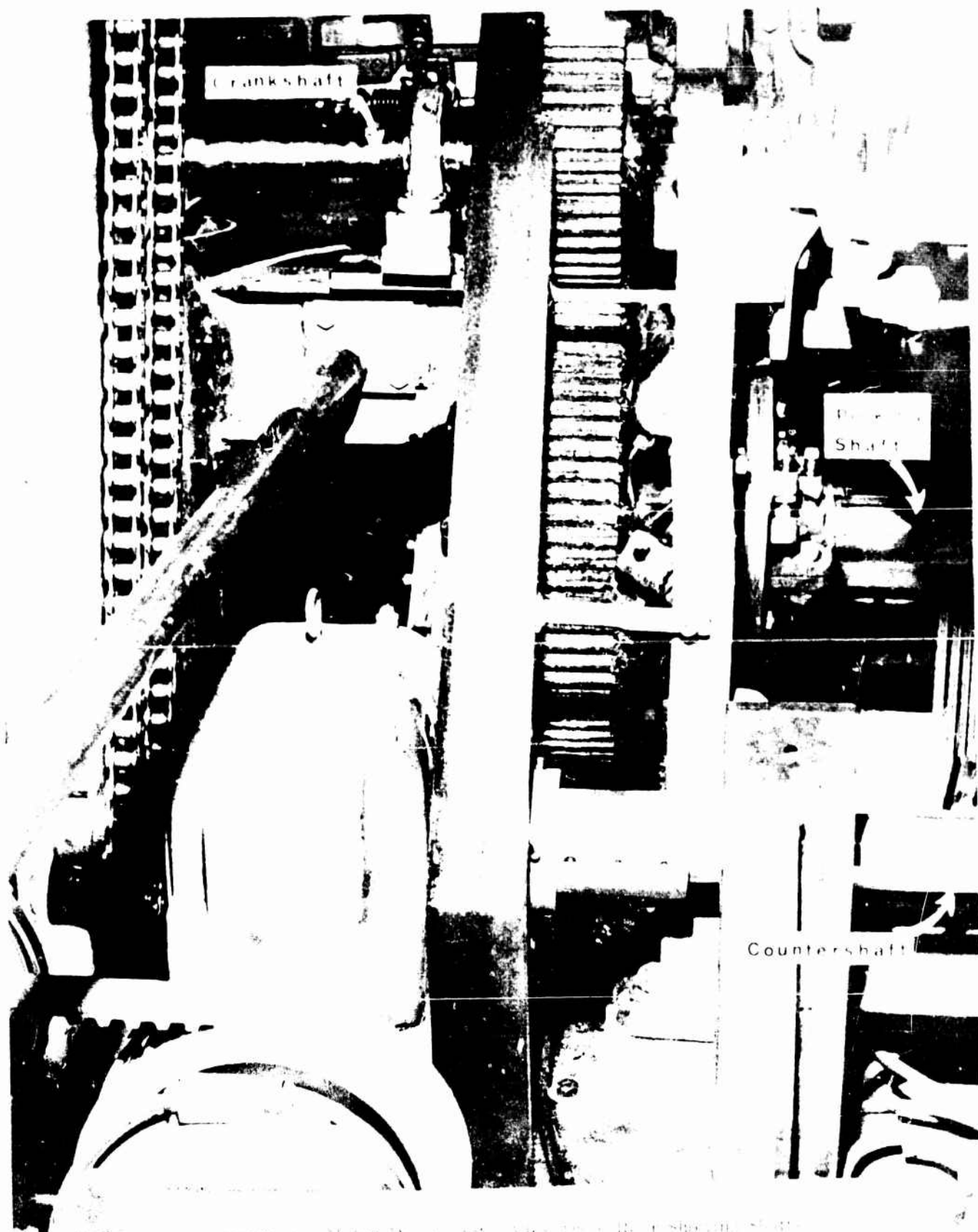


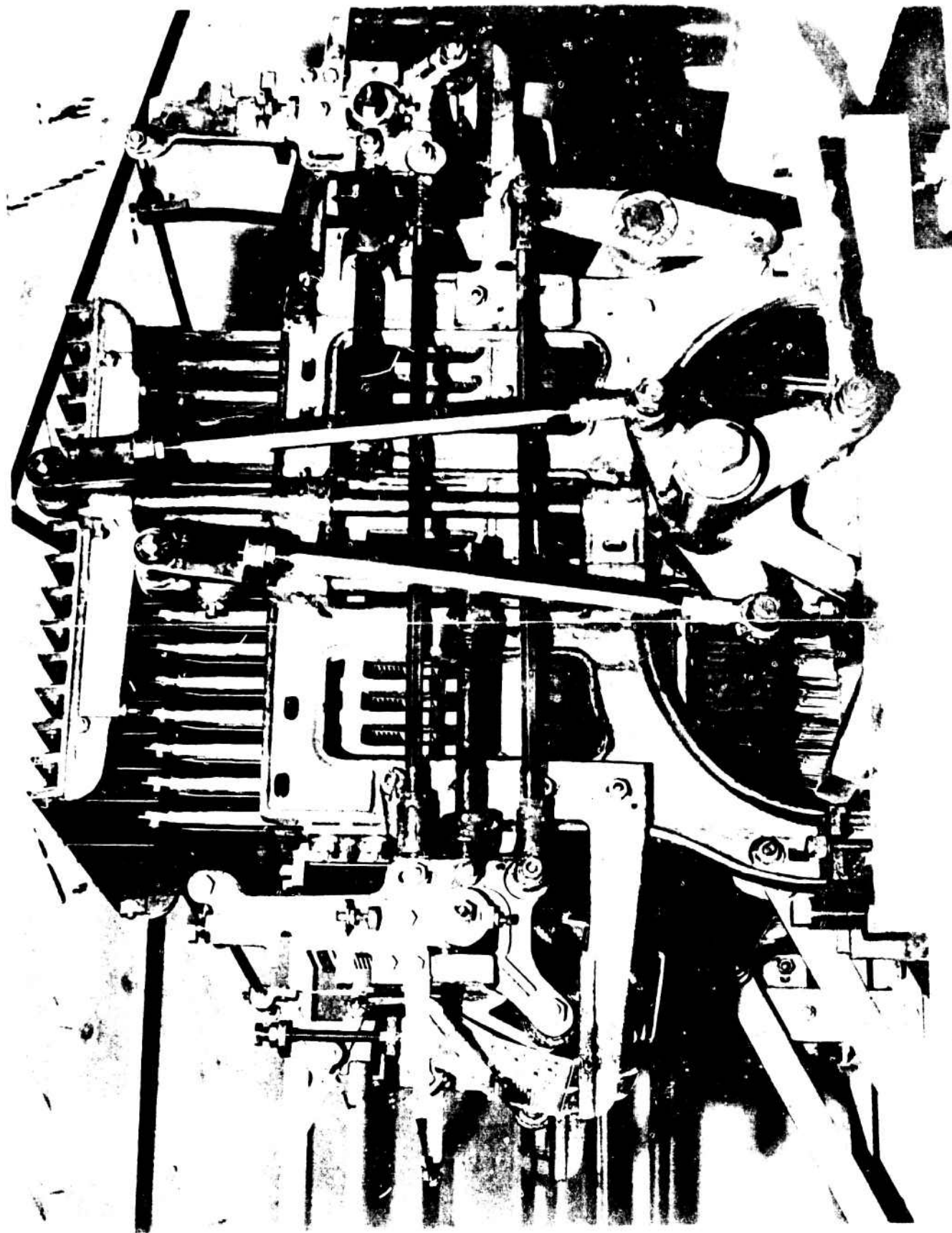
FIGURE 1. Motor Drive Unit - View from Right Side of Motor

4.3.9 Cont'd.

caused by the raising and lowering of the lingoes, and before the additional concrete piers were poured, the picking action of the power train also caused vibration problems. Additional steel columns were added to the structure, and the overall unit was additionally anchored to the wall of the building. By the time the loom modifications and loom setup were complete, the gantry was a substantial structure. Figures 9 and 10 show the left and right Jacquard heads mounted on the gantry and Figure 11 shows both heads. Figures 12 and 13 show the gear drives for the left and right heads.

4.3.10 During the period that the power was being increased, a considerable number of cast iron loom parts became overstressed and failed and these were replaced with parts fabricated from steel. An example of this is the cast iron frog which activates the loom stop motion, which in turn is activated if the shuttle fails to enter the shuttle box properly. Initially the loom was stopped by a mechanical linkage from the frog to the mechanical clutch. Because of the added power, the cast iron frogs broke repeatedly when hit by the lay beam. These were replaced by steel parts. Additionally, microswitches were added to activate the electromagnetic clutch and brake to replace the original mechanical linkage.

4.3.11 The weaving of a double-wall inflatable fabric involves the weaving of two faces at different rates of speed. On a previous contract, the required length differential between the inside and outside faces was accomplished by using two



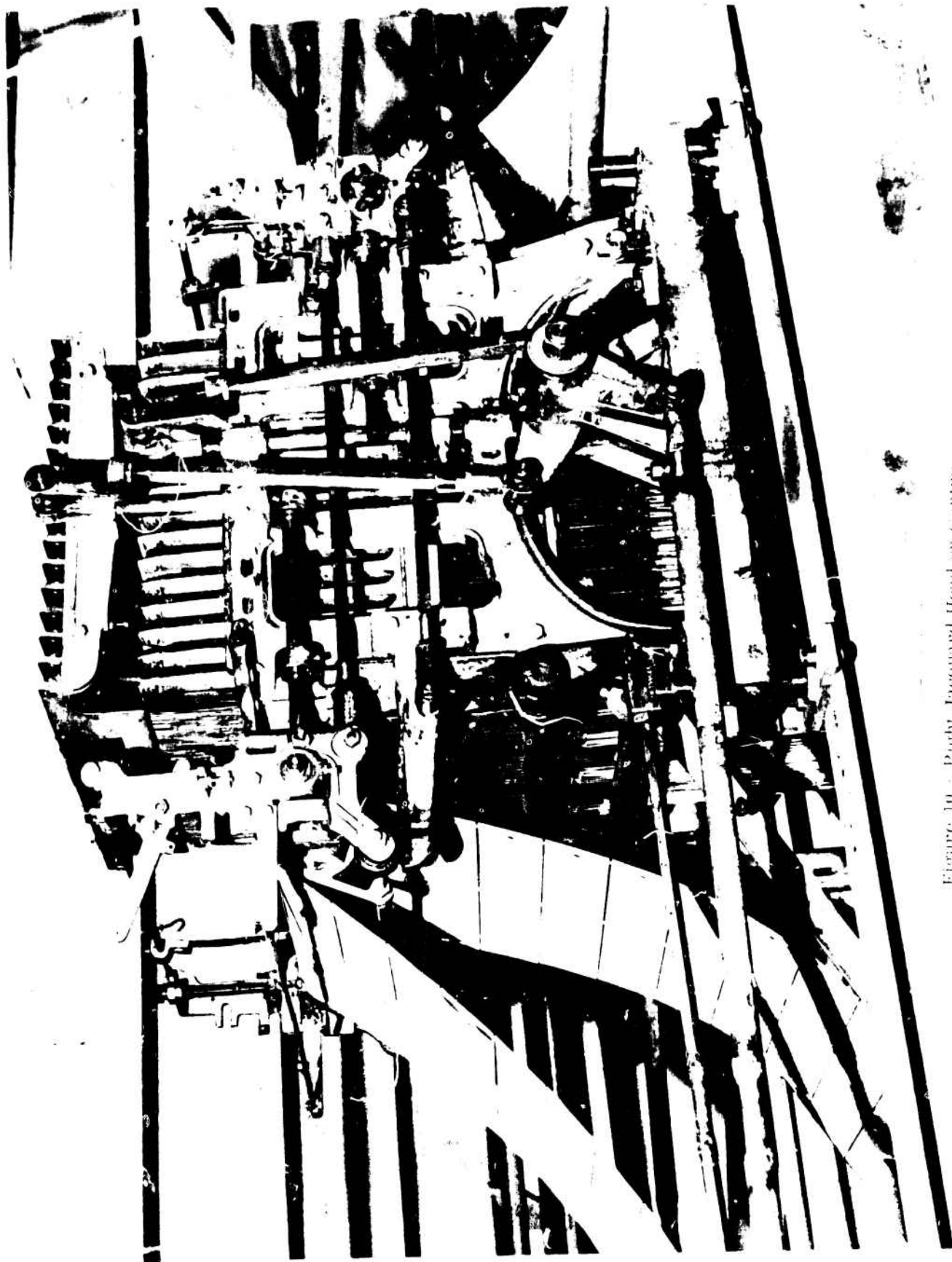
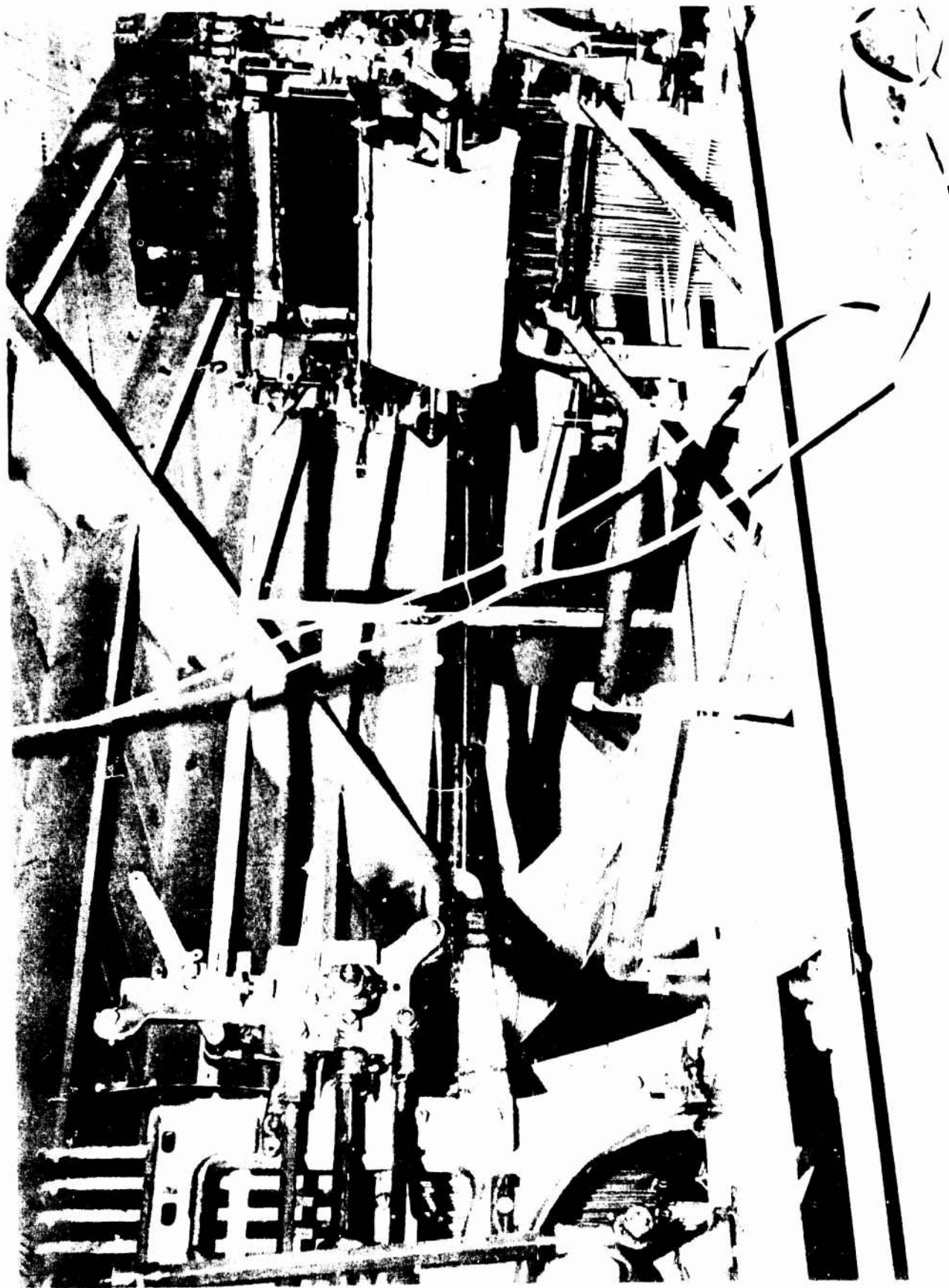


Figure 10 - Right Jacquard Head on Cartage



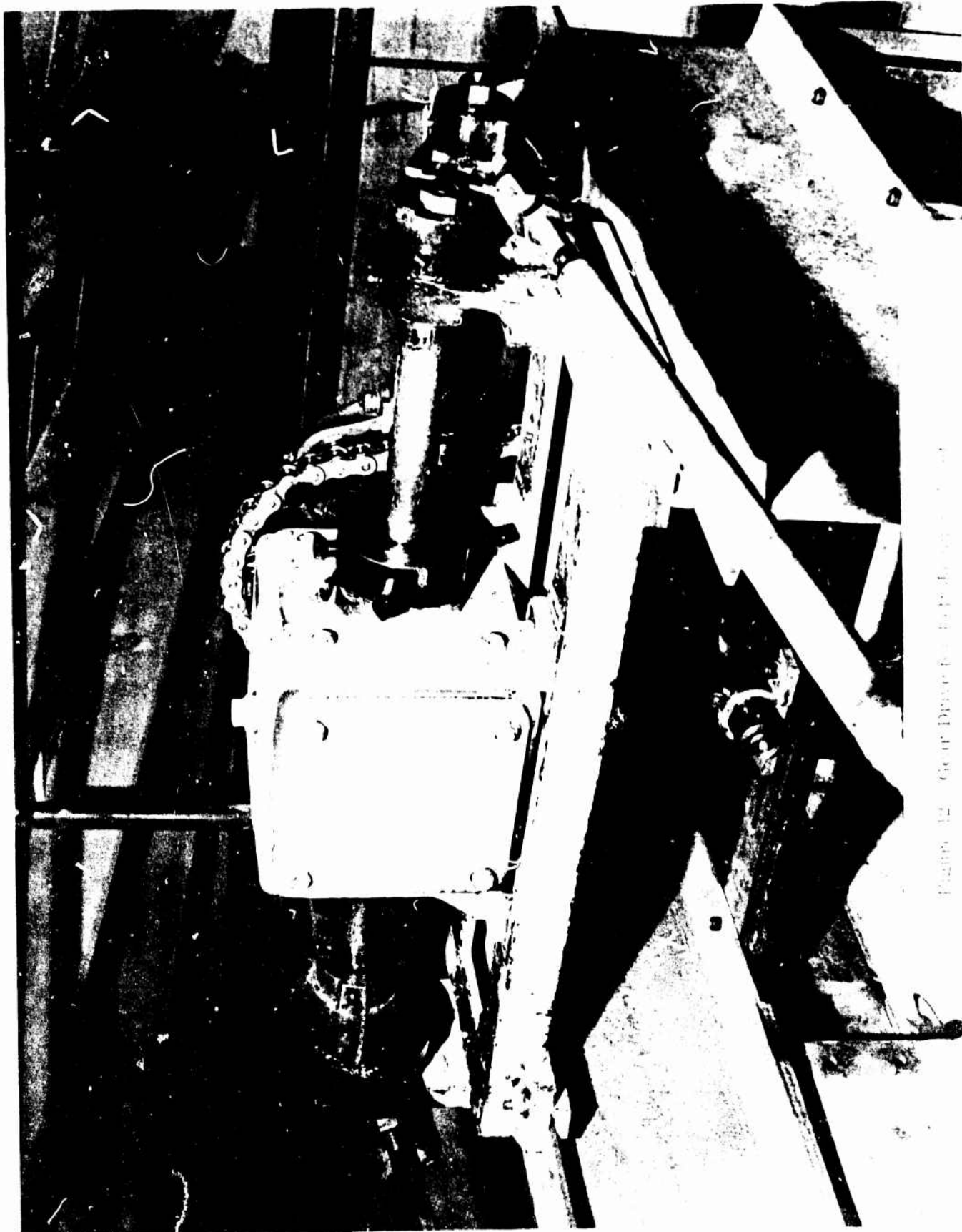


Figure 12 Gear Drive for the Propeller

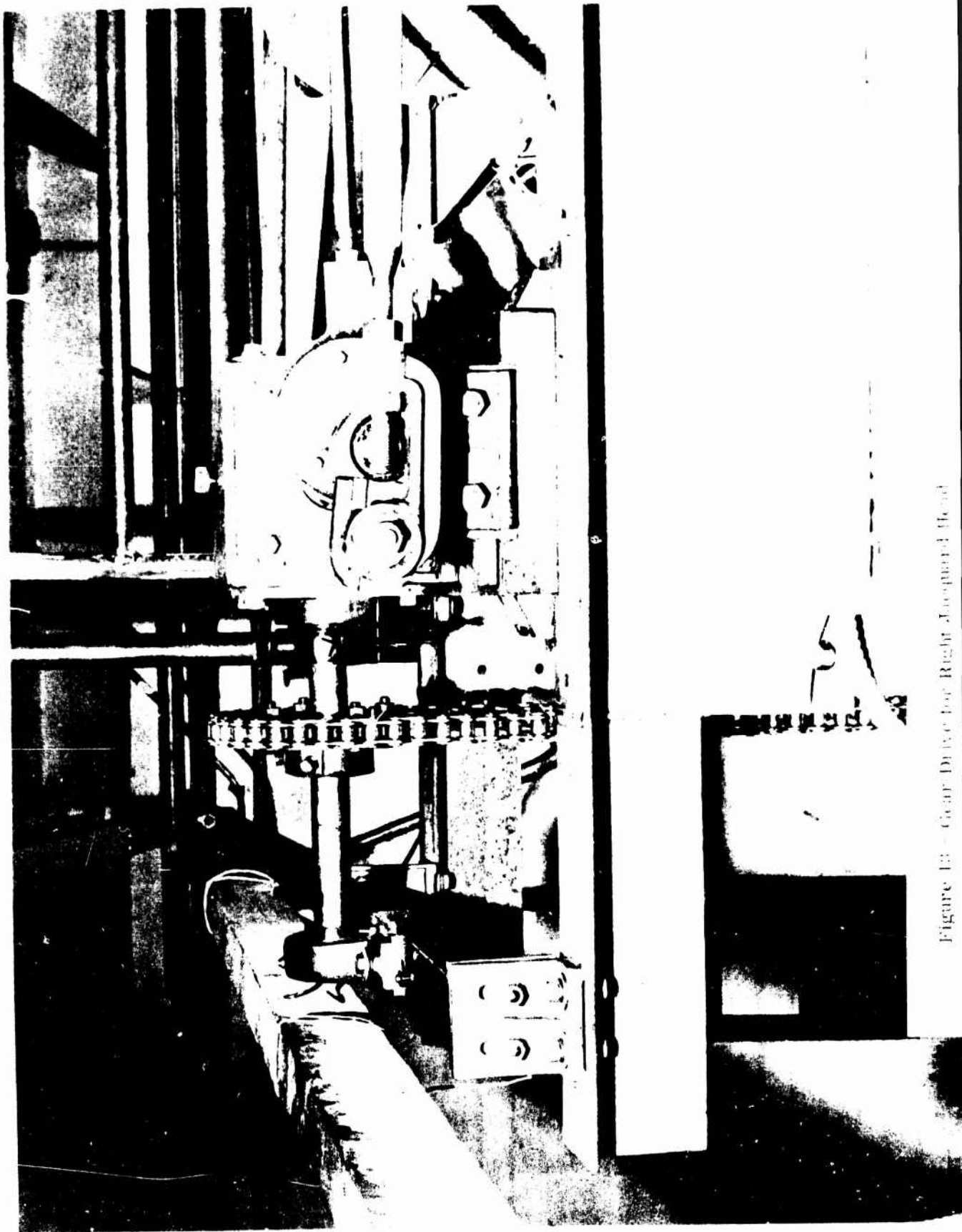


Figure 13 - Gear Drive for Right Jacquard Head

4.3.11 Cont'd.

take up, or draw rolls. The principle of this concept is shown schematically in Figure 14. As can be seen, the upper draw roll engages and pulls the outer fabric at the rate corresponding to the roll's surface speed and allows the inner fabric to slide over the surface of the outer fabric. The bottom draw roll engages and pulls the inner fabric at its proper surface speed and allows the outer fabric to slide over the surface of the inner fabric. In that contract, the ratio of their diameters was the same as the ratio of the corresponding inner and outer radii of the face fabrics when measured from the respective lines where the ribs joined the faces. This arrangement simplified the take-up roll drive since both rolls could be driven at the same rotational speed using 1:1 coupling gears. For the new program, the 10-foot-wide radius was to be measured from the inflated reference surface (Figure 3), and it was decided to incorporate more flexibility into the take up system by making two draw rolls of identical 6.366" diameter, or 20" circumference. This required that the rotational speeds differ, and the drive system used is as shown schematically in Figure 15. A 108-tooth ratchet was mounted on shaft A and this ratchet was advanced one tooth via a ratchet arm activated at each pick from a cam mounted on the crankshaft of the loom. A 12-tooth gear mounted on shaft A drove a 36-tooth gear on shaft B, and an 18-tooth gear on shaft B was thus made to drive a 96-tooth gear on shaft C. The reduction from shaft A to shaft C, therefore, was $\frac{12}{36} \times \frac{18}{96} = \frac{1}{16}$ or 16:1. The top draw roll which

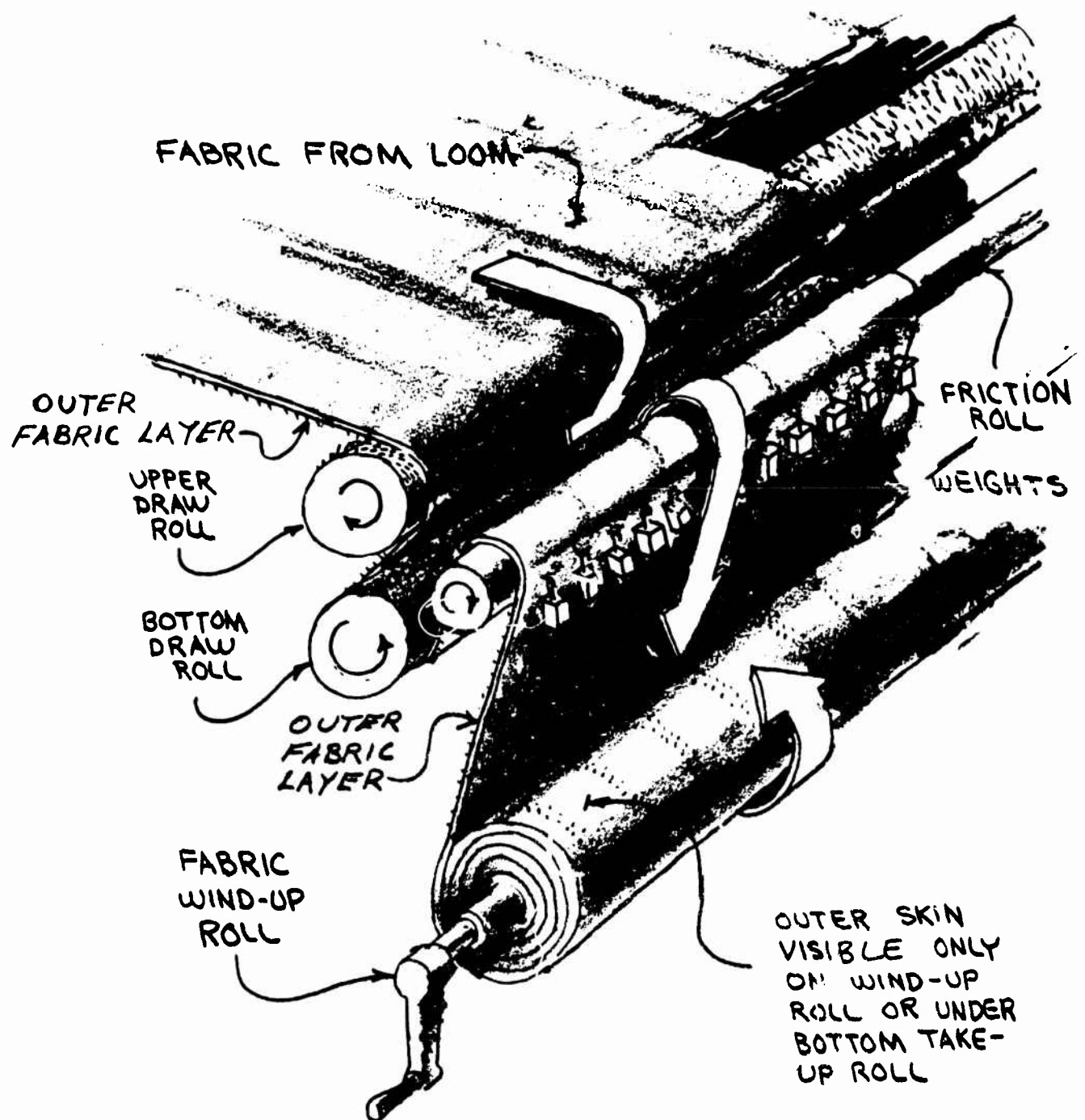


Figure 14 - Schematic Arrangement of Draw Rolls Used to Form Inflatable Fabric

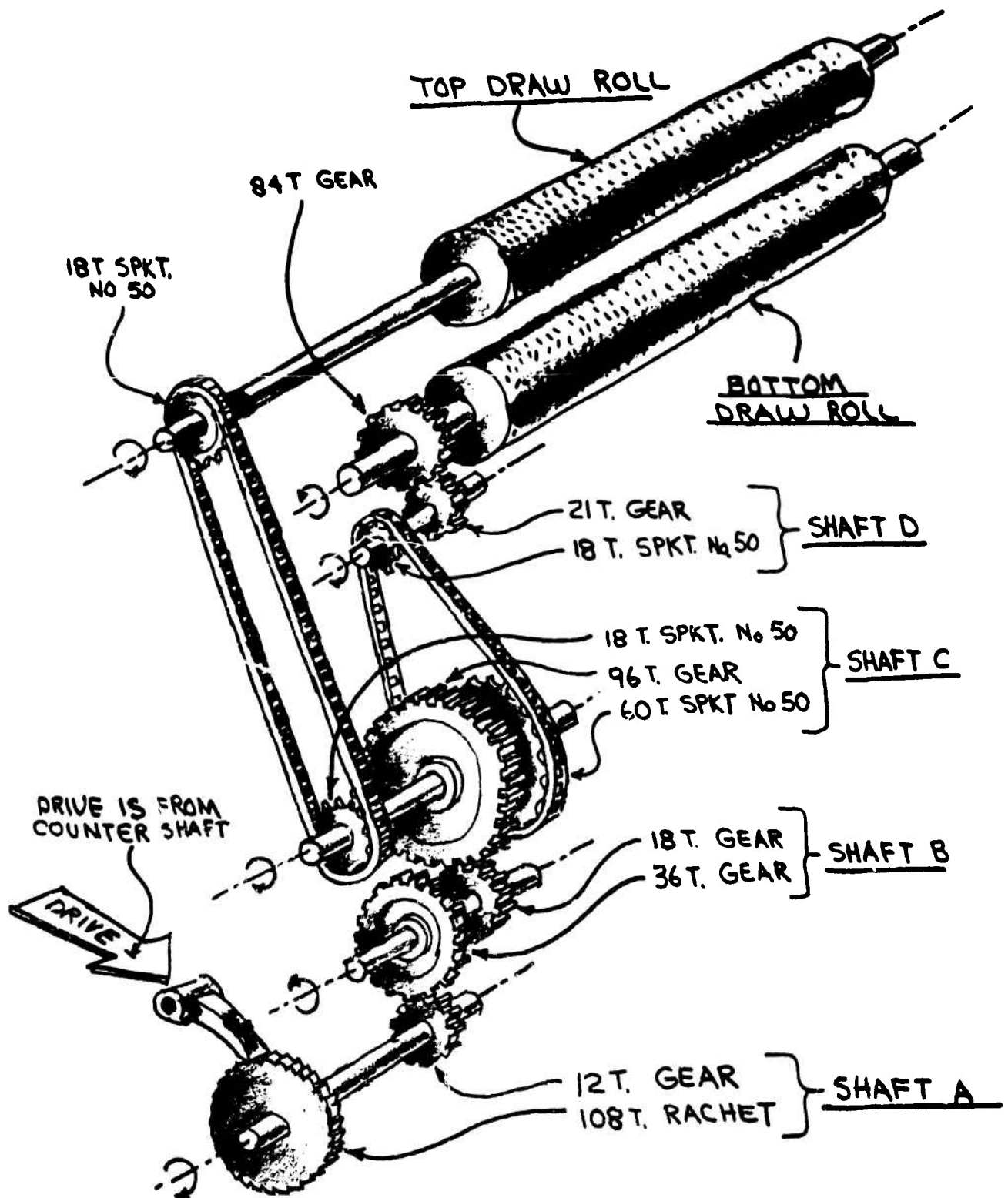


Figure 15 - Schematic Arrangement of Drive System for Draw Rolls

4.3.11 Cont'd.

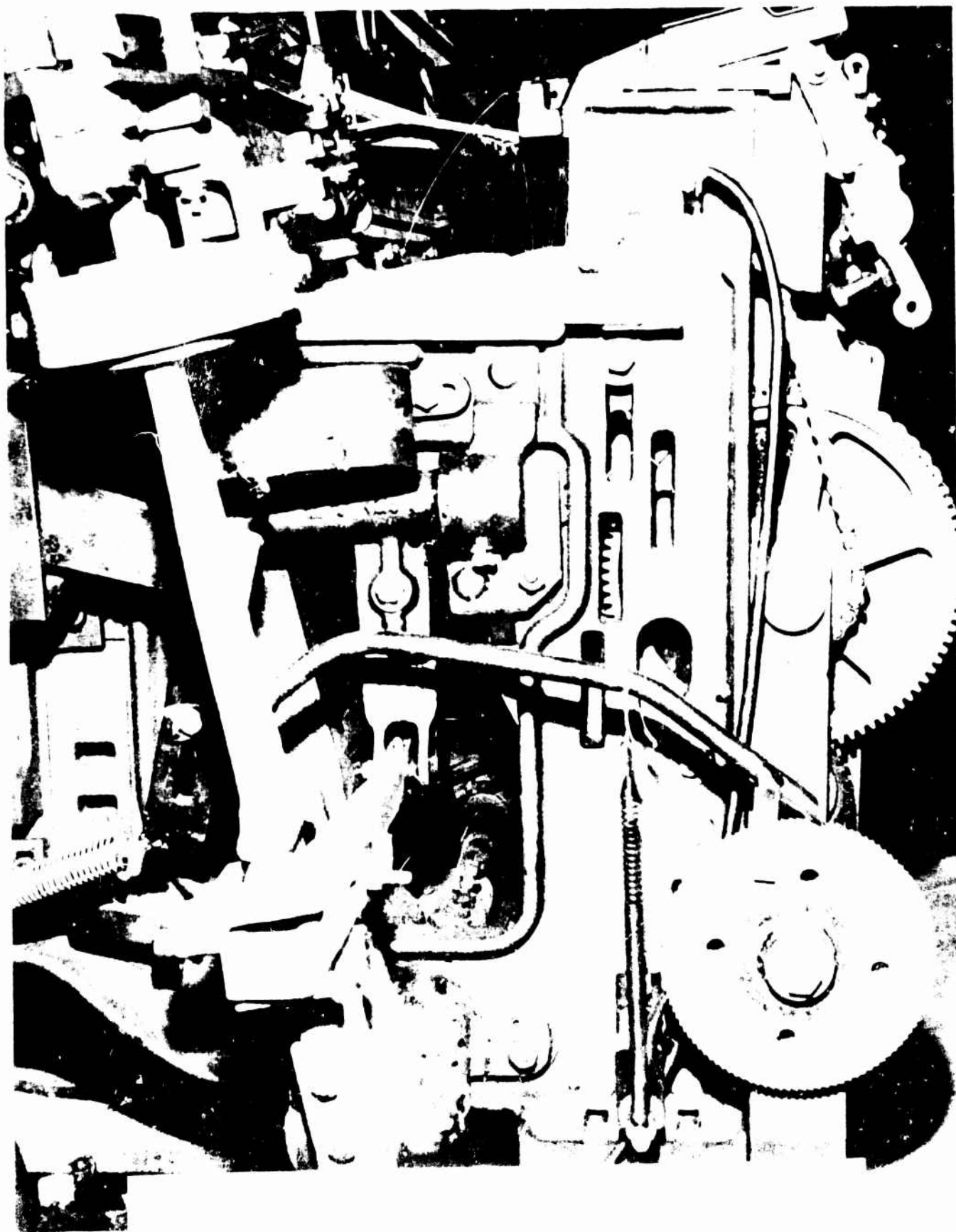
controlled the top fabric face was driven from shaft C through a chain and sprocket arrangement with both sprockets being of the same size, and the top roll rotation at the same speed as shaft C. Thus, 16 revolutions of the 108-tooth ratchet of shaft A would be required for each revolution of the top roll which is equivalent to $16 \times 108 = 1728$ single tooth advances of the ratchet. With the circumference of the top roll at 20", each single tooth advance was $\frac{20}{1728} = 0.011574$ " on the top draw roll surface. Since two fill yarns were to be inserted in each fabric layer for every eight picks, or ratchet advances, the fill yarn spacing for the outer face was $4 \times 0.011574 = 0.046296$ inches per pick or $\frac{1}{0.046296} = 21.6$ picks per inch. For the bottom roll drive a 60-tooth number 50 chain sprocket on shaft C drove an 18-tooth sprocket on shaft D, and on the same shaft a 21-tooth gear drove an 84-tooth gear on the bottom roll. For each tooth advance of the ratchet, the bottom roll surface advance was $\frac{1}{1728} \times \frac{60}{18} \times \frac{21}{18} \times 20 = 0.009645$ ". The advance for the inner face was $4 \times 0.009645 = 0.03858$ inches per pick, or $\frac{1}{0.03858} = 25.9$ picks per inch.

4.3.12 The ratio of pick counts between the two faces was $\frac{25.9}{21.6} = 1.199$, or 1:1.199, inner to outer faces. From the calculations relating to the inflated cell dimensions (See Appendix 2), it appeared that the major diameter of the outermost cells of the fabric would be $10.46 \times 2 = 20.92$ " or 1.743 feet. Based on an inflated radius of the structure of 10' 0" at the inner face, the outer face should be $10' + 1.743' = 11.743$ feet. This corresponds to a ratio of $\frac{11.743}{10} = 1.174$, or 1:1.174, inner to outer faces.

4.3.12 Cont'd.

From past experience it was found that the ratio of the pick counts off the loom, with fabric relaxed, was slightly lower than the ratio as measured while on the loom. This is attributed to friction between the faces of the fabric as it goes around the top roll, and this friction tends to deliver the inner face to the bottom roll with less tension than if no friction existed. With this in mind, the take up mechanism drive train components were selected to yield the 1:1.199 ratio which was slightly higher than the ratio calculated from the inflated dimensions. Figures 16 and 17 are photographs of this drive train.

- 4.3.13 To insure the maintenance of the correct ratio of inside to outside fabric length, it was necessary to utilize a positive draw roll covering. Conventional draw roll coverings are usually made of sandpaper, or of cork or rubber in which is embedded a gritty particulate substance. An alternate arrangement is one in which the draw roll is surfaced with a number of pins driven radially into the draw roll. It was felt that the conventional abrasive types of coverings would not function properly under the requirement that one fabric layer must be pulled positively around the roll while the other layer slips over the first fabric layer. The abrasive surface was not positive enough to drive the layer closest to the roll. Pin rolls were also unsuitable since the pins would protrude through both faces and the slippage would not occur, thereby resulting in both faces having the same length. Various types of coverings were tried, and the best results were obtained by using card clothing of a type normally used on the cylinders of a wool card.



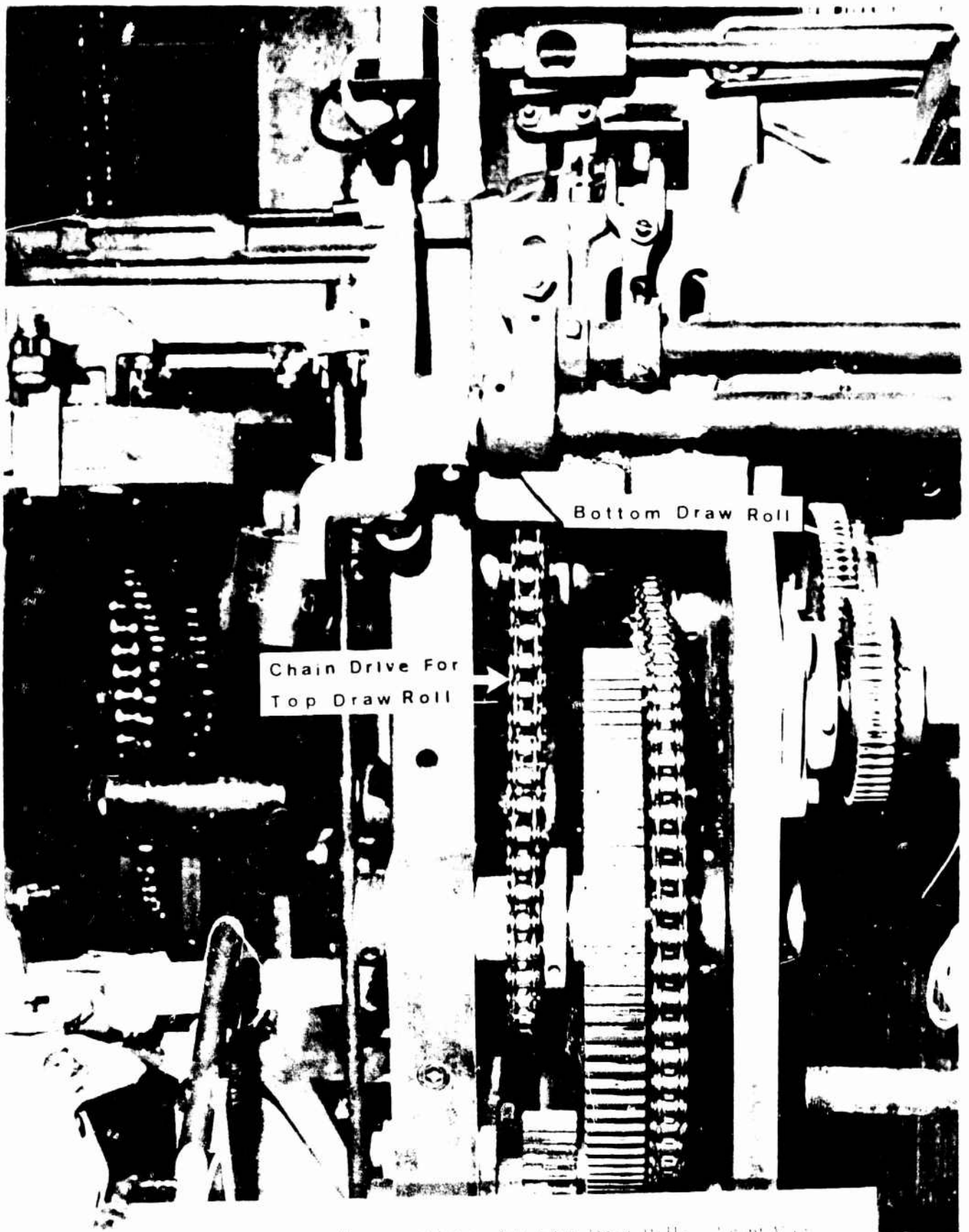


Fig. 1. Chain drive for top draw rolls. Front view.

4.3.13 Cont'd.

This clothing consists of a flexible fabric base approximately 5/32" thick with wire staples driven through the base and projecting above the surface as shown in Figure 18. The wire staples are formed from No. 32 wire (approx. 0.010" diameter) with a knee bend as shown. The particular construction selected had a coverage of 360 points per square inch and was found to provide the positive traction required without projecting through to the second layer.

4.3.14 To minimize the possibility of deflection in the reed and reed cap because of the long span, the cap in the horizontal plane was reinforced by means of a truss consisting of a 5/8"-diameter rod kept under tension. Not anticipated, however, was a tendency for the reed cap to deflect vertically at the center. During the preliminary weave trials this vertical deflection occurred allowing the reed to become loose. A 1/2"-diameter rod truss was then installed to keep pressure in the vertical plane of the reed cap. A portion of the reinforced reed cap is seen in Figure 19.

4.4 Loom and Creel Set Up

As covered earlier, much of the setup task involved the loom modifications. Other tasks of the setup phase included creeling, tying in the heads, drawing in the yarn, loom start-up and debugging.

4.4.1 Nine creels were loaded with 13,244 5/8" diameter braider tube packages wound with the pretreated Dacron yarn, each package having about 900 feet of yarn. The use of creels rather than warp beams was necessary because all warp yarns were not going to be pulled through the loom at the same speed. The top face warp yarns were to travel at one speed, the bottom face warp

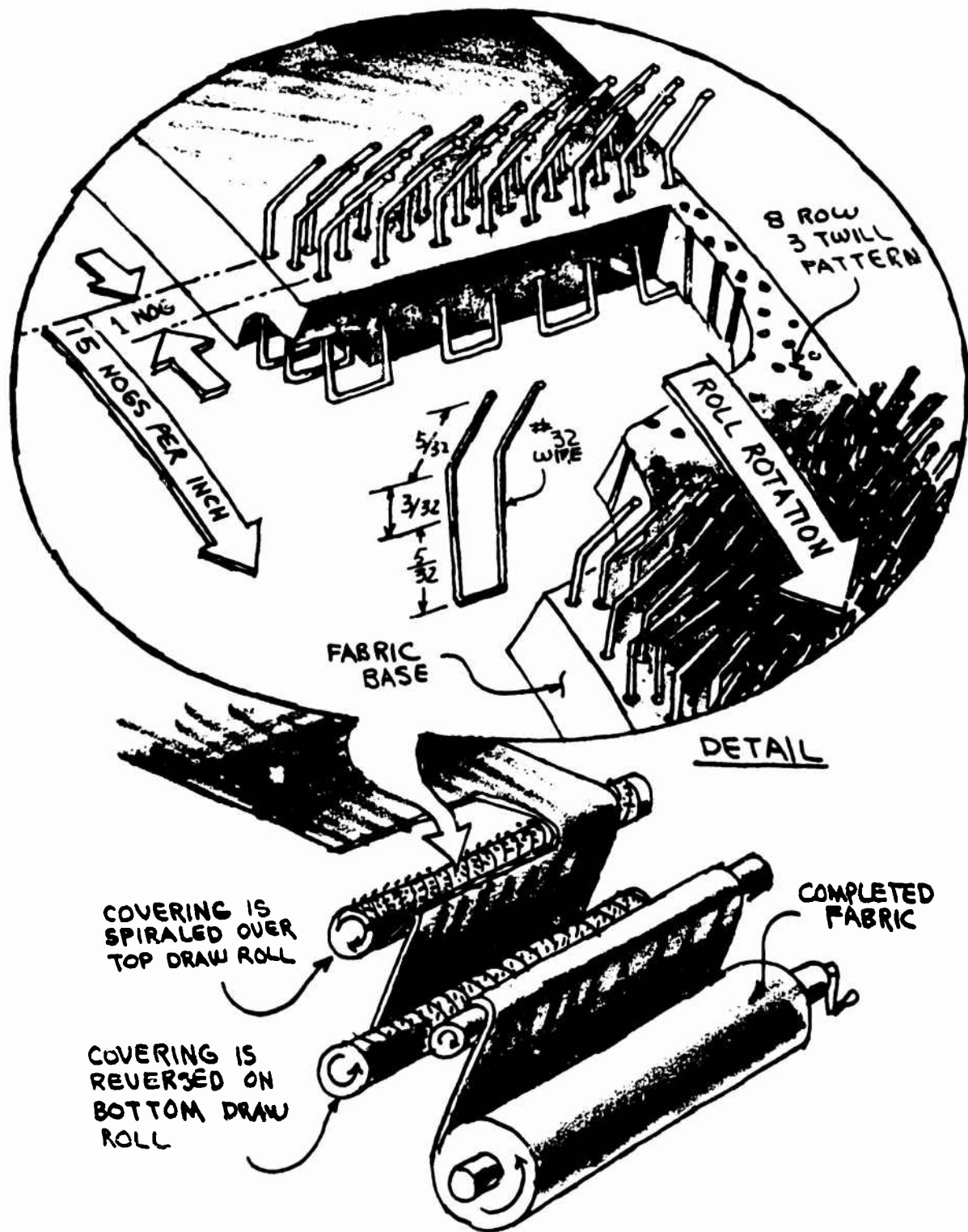
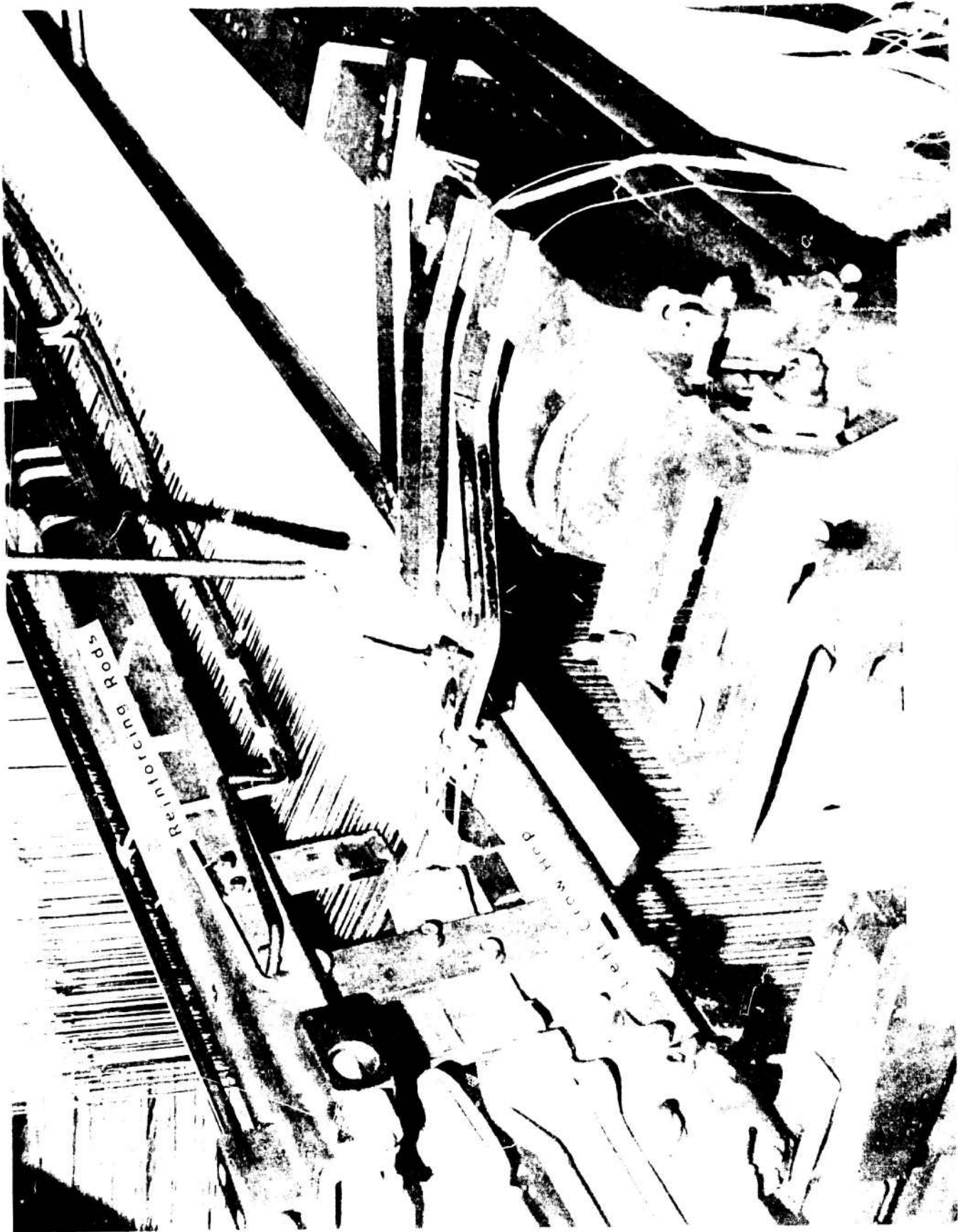


Figure 18 - Detail of Draw Roll Covering



4.4.1 Cont'd.

yarns at another speed, and the rib warp yarns at varying speeds. Each package was fitted with a tube runner which in turn was positioned on a spindle of a creel. Each yarn end was individually tensioned by use of U shaped weights and drawn into the loom. On its trip, each yarn passed through an eyelet of the creel, lease rods, its designated heddle and reed dent. A schematic of this arrangement is shown in Figure 20. Some of the creels used in the set up are shown in Figures 21 and 22. Yarns passing through the lease rods are shown in Figure 23. A view beneath the yarns passing through the lease rods is seen in Figure 24. This view, taken from the left side of the loom also shows the power unit of the loom and the various shafts previously described.

4.4.2 As previously noted, to make the two Jacquard heads work for the 13000 + warp ends it was necessary to tie groupings of up to eight heddles to each hook with an average grouping of six per hook. Before the heads were finally positioned over the loom, a preliminary series of tests were made on a special rig by simulating the extreme conditions that were expected to be encountered with the harness lines coming down from the hooks at relatively high angles. There was concern that this large angle and the crowding of the lines might interfere with the ability of the lines to move freely. From these tests, it was decided to locate the heads as closely as possible to the ceiling which made the vertical distance between the bottom of the heads and the top of the loom approximately ten feet, and this distance was felt to be adequate based on the preliminary

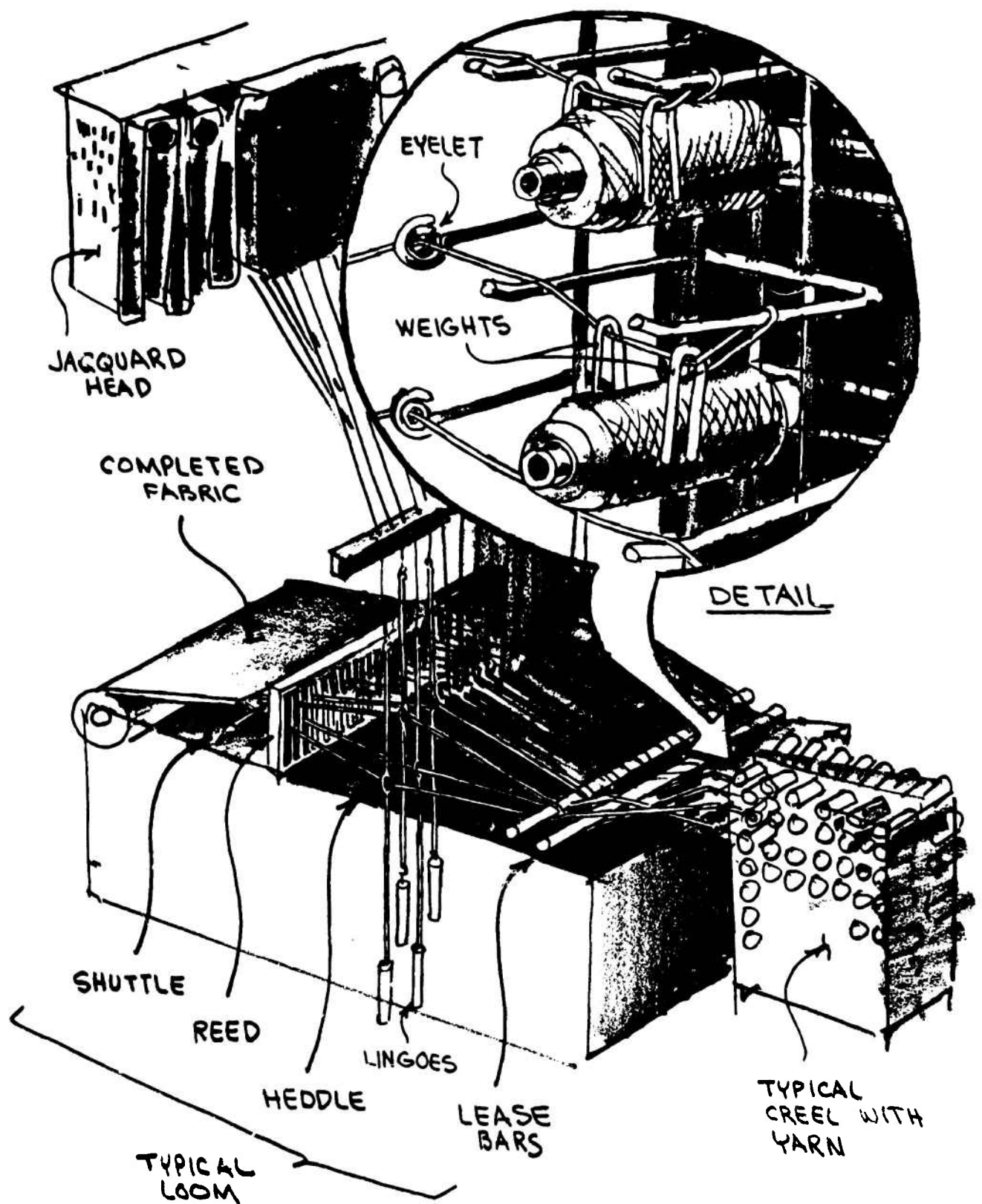


Figure 20 - Typical Yarn Path in Loom Set Up

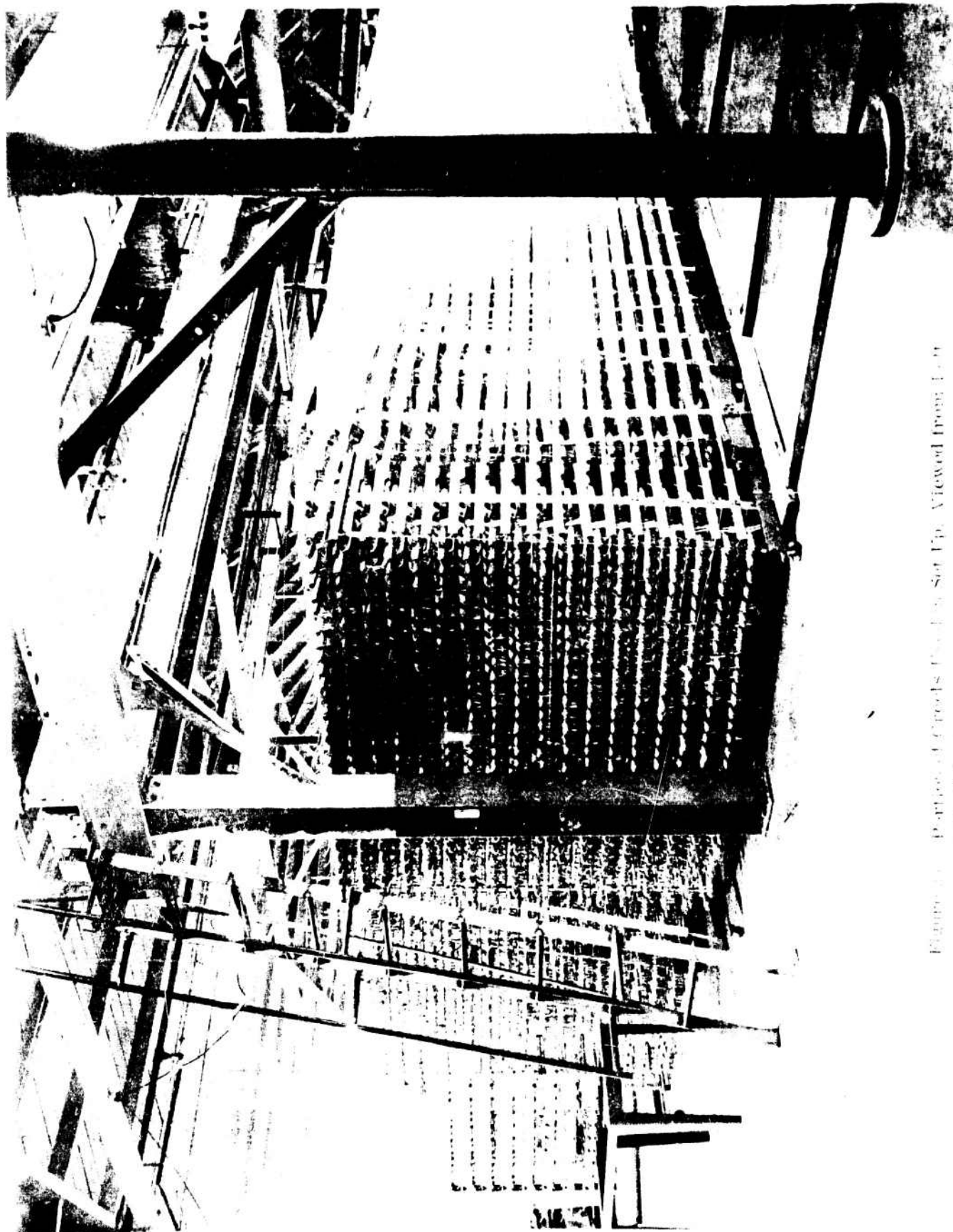


Figure 1. Part of a filter made by Set Up. Viewed from Top
Side of Figure

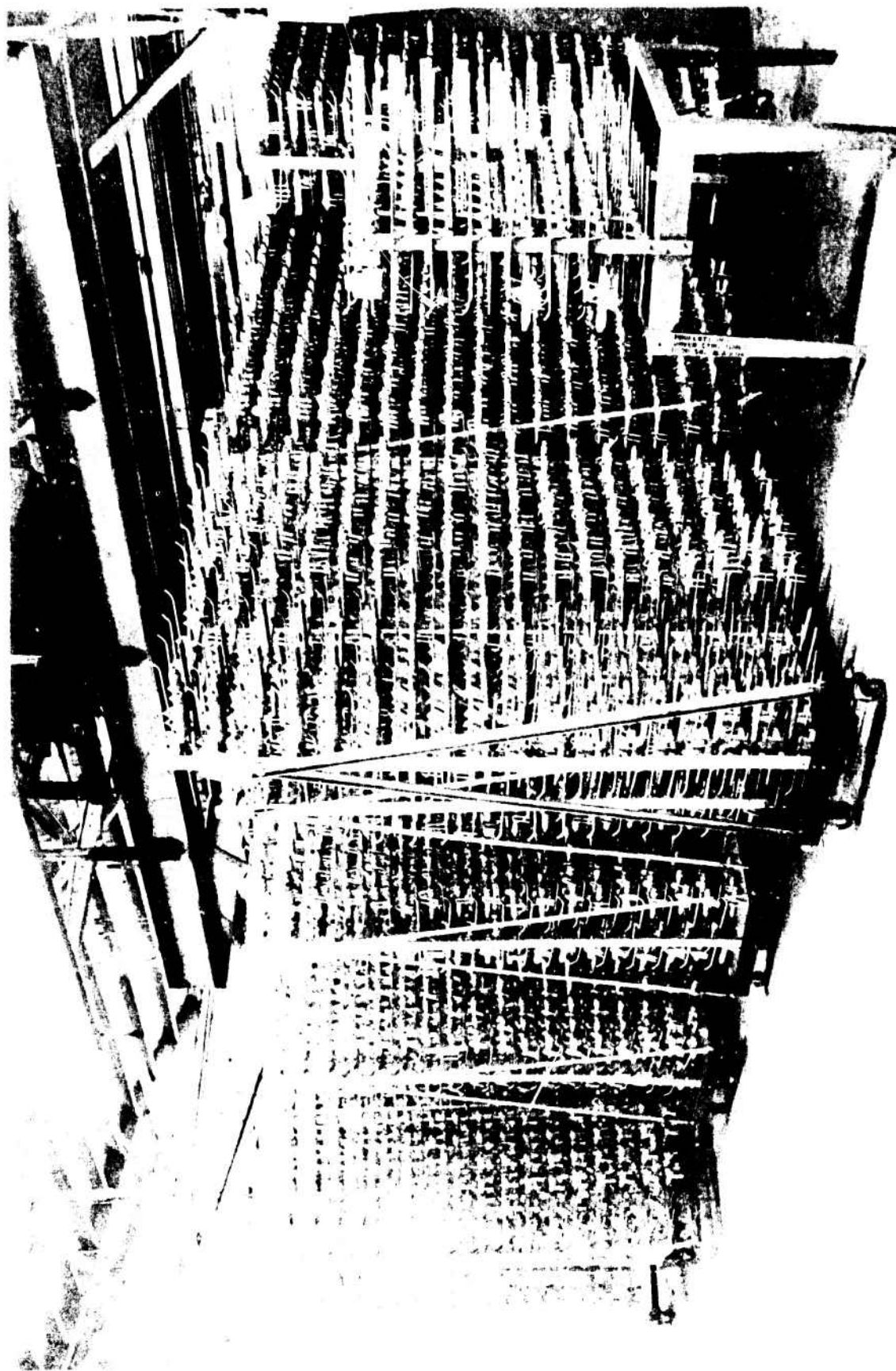


Figure 22. Position of Cables Used in Set Up. View From Left
Rear of Loom

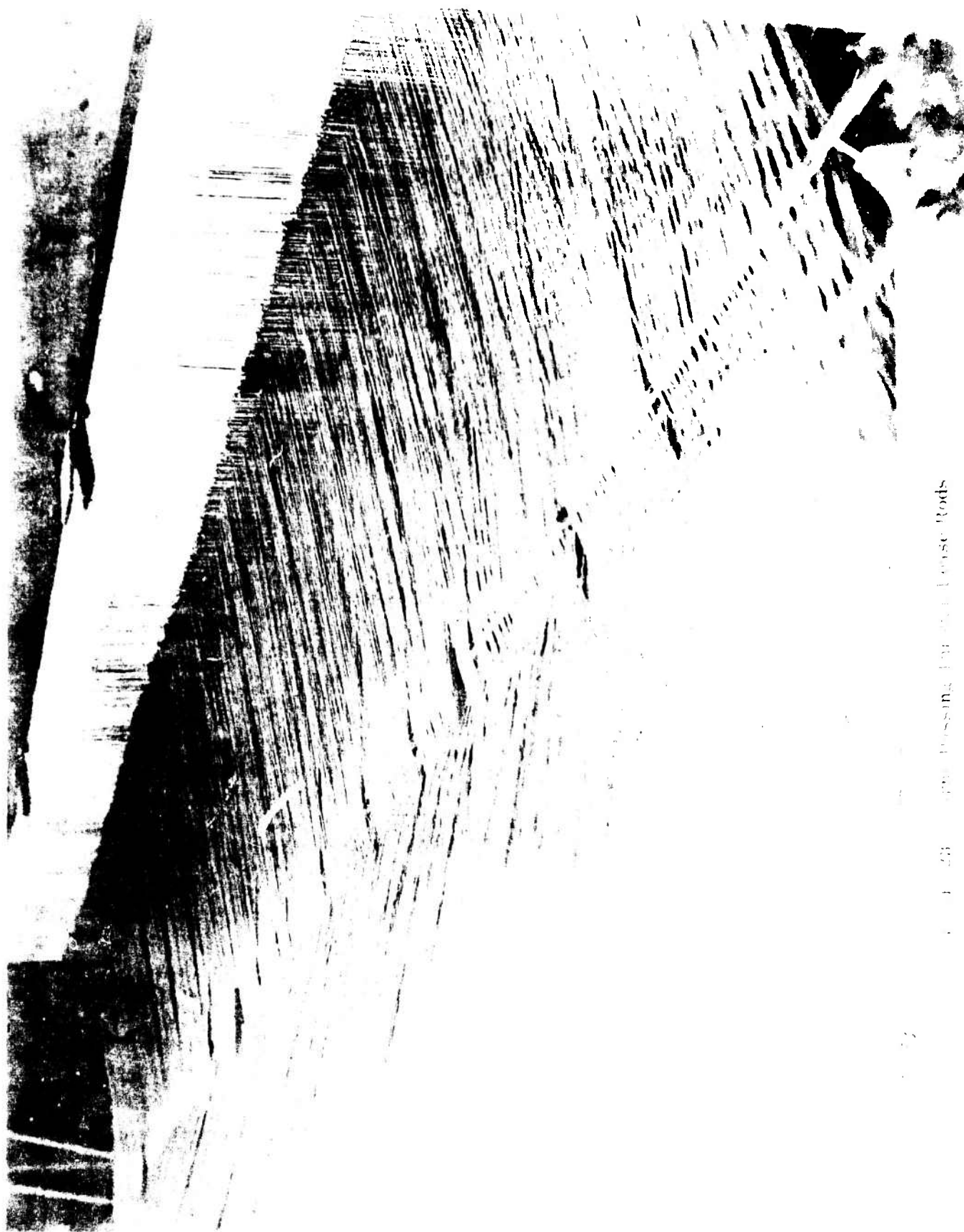


Fig. 1. 23. Ship's hull, showing the use of rods.

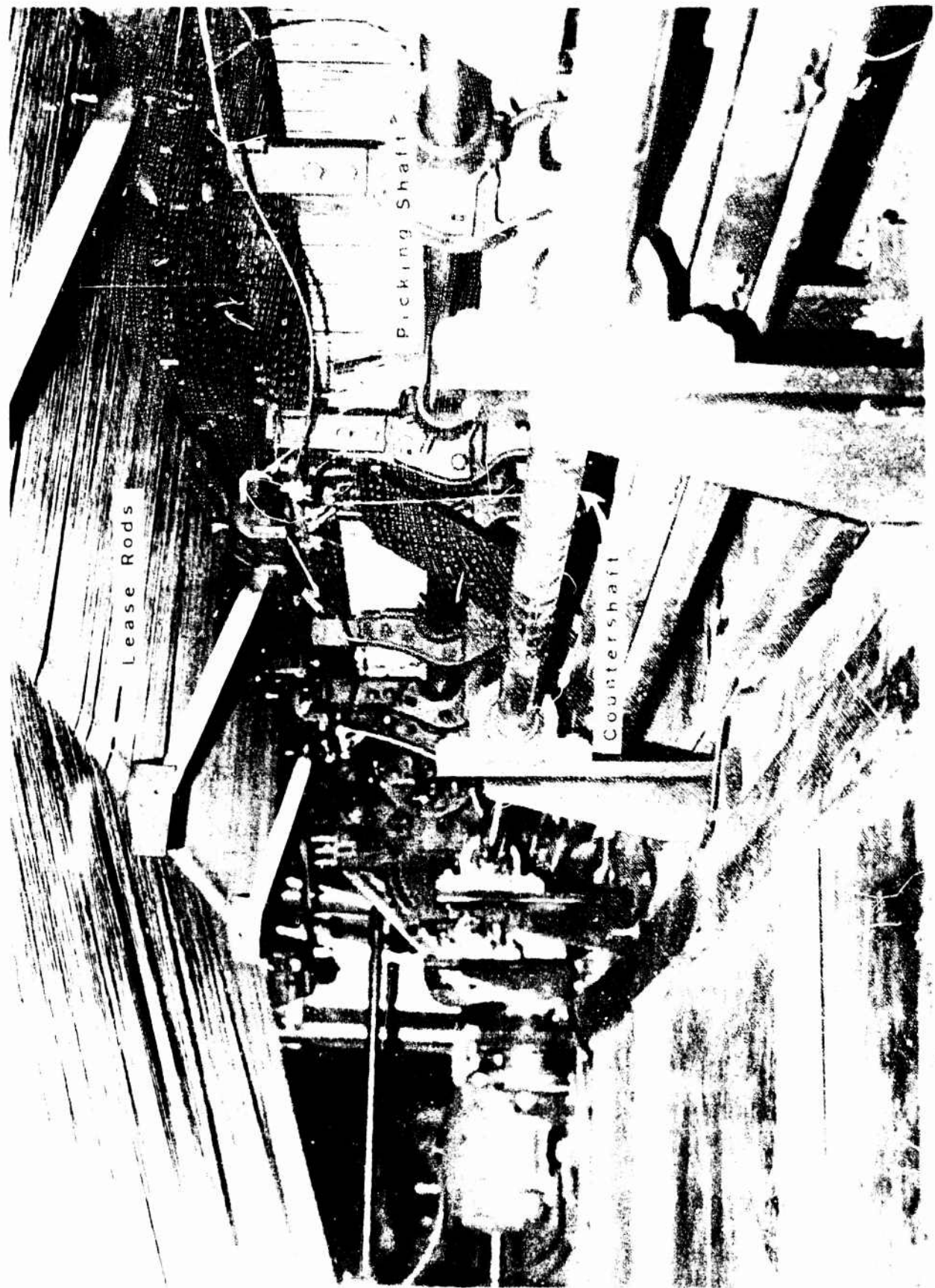


Figure 3.1 - View 3 mile north from Sheeping - Picking - Looming - Lease Rods

4.4.2 Cont'd.

tests. The main tie up was then started wherein the harness lines were tied to the neck cords which were in turn connected to the hooks of the Jacquard heads. The harness lines were then threaded through the proper designated holes of the comberboards below, and each harness line was tied to a heddle, below which was suspended a lingo. A view of the harness lines of the completed tie up is seen in Figure 25. Figure 26 shows a portion of the lingoes and as can be seen, they presented a very crowded condition. This condition caused a good deal of the weaving problems as will be noted later in this report.

4.4.3 The eyes of all the heddles were leveled to a common plane and the warp yarns drawn through. The yarns were then drawn through the reed, pulled around the draw rolls and tied in groups of several hundred with a weight tied to each group. The loom was now ready for start up and the next step was to adjust the timing of the picking motion, the lay motion and the Jacquard heads relative to each other. As it developed, this timing was very critical and a considerable period of several weeks elapsed before this was accomplished. During this period an outside consultant familiar with the adjustment problems of this type loom was engaged to assist in the timing problem, and with his help as well as the dilligence of the operators assigned to the program, the timing was solved.

4.5 Weaving

4.5.1 In conventional weaving, the fabric after being drawn through the loom, would normally be wound onto a roll of from 50 to 100 yards or more. This roll would usually be driven through





4.5.1 Cont'd.

a slip clutch to accommodate the growing diameter of the product. Because of the relatively short lengths of fabric required per part it was decided to roll the fabric by hand on to a pipe core. In order to maintain tension on the fabric and thus insure that the draw roll previously described would advance the fabric by the correct increment of advance, a 4"-diameter roll, surfaced with friction material, was mounted adjacent to the bottom draw roll and was driven by a set of gears from the bottom draw roll. The ratio of teeth in these gears was such that the surface speed of the 4" diameter friction roll was 10% higher than the surface speed of the bottom draw roll. Weights of approximately 2 lb each were pinned to the fabric at each tab end and at each locking seam area, and these weights were moved manually as the fabric advanced.

4.5.2 The direction of rotation of the pipe wind up roll was selected so that the upper or outer fabric face was outermost on this roll. This arrangement provided the earliest opportunity for the operator to inspect the outer face, since visual access to this face was almost impossible prior to wind up. During weaving, the inside face was topmost as the fabric came through the loom on to the draw rolls. With this wind up roll arrangement, the outer fabric could not be observed for about an hour after it was woven when the loom was operating properly. This, of course, made it difficult to correct defect causes on the loom while they were affecting the outer fabric. The arrangement of the 4" diameter friction roll, weights and hand wound cloth roll, as well as the relative position of the cloth layers are shown in

4.5.2 Cont'd.

Figure 14. Figure 27 is a photograph showing a portion of the lower draw roll, friction roll and weights on the outer fabric face viewed from the right side of the loom. Figure 28 is a view of a portion of the inner fabric face as would be observed by the operator during weaving.

4.5.3 During weaving, one-foot units of length were marked and numbered on the right hand tab of the inner face. When the required length of each part was woven, a shuttle bobbin containing white glass yarn was inserted and the weaving continued until the area of contrasting color came around the friction roll, at which point the finished part was cut from the loom.

4.5.4 Numerous problems were encountered during the actual weaving, many of which were attributable to the Jacquard operation. Because of the high density and crowding of heddles and lingoes, many warp yarns not programmed to be raised for a particular pick would actually be raised because their lingoes were dragged up by the friction of adjacent lingoes. Also, some of the raised yarns would not always get lowered for the same reason. This condition would cause either face to become locked to a web or to the other face and resulted in fabric defects that subsequently had to be repaired.

4.5.5 In the early stages of the weaving phase, these locking problems were so serious that the fabric faces were unable to slide over each other adequately as they were being pulled around the draw rolls. This, of course, resulted in fabric having improper





Figure 2. Fabric coming from the factory is very noisy and is not
 longer in a folded state.

4.5.5 Cont'd.

contour since it is imperative that the fabrics can slide relative to each other. The crowded lingo condition also put excessive loads on the hooks of the Jacquard heads. With each hook normally lifting 6 or 8 lingo, the loads were sometimes doubled because of the unwanted raising of adjacent lingo, and this often resulted in Jacquard hooks being bent. These bent hooks became entangled with adjacent hooks and this further aggravated the proper raising and lowering of warp yarns, and this in turn caused wide bands of locked-together fabric. Each of these occurrences resulted in a delay of several hours while the damaged hooks were being repaired or replaced.

4.5.6 Several things were done to alleviate the crowded heddle and lingo problem. First, it was noted that the tendency of the fabric plies to lock together occurred principally in the areas of the locks formed between the faces and webs. These areas were zones of maximum warp density and were designated to be a basket weave in which two adjacent warp yarns would operate as a pair and raise and lower at the same time. Each yarn of these pairs had been assigned to a separate heddle, harness cord, and lingo as is conventionally done. After a redesign, each pair of these warp yarns was drawn through a single heddle and this made it possible to eliminate over 1,000 harness cords, heddles, and lingo, or nearly 10% of the original quantity, and this change proved to be very effective in reducing the fabric locking problem. However, lingo crowding was still a problem in the balance of the areas

4.5.6 Cont'd.

and this was overcome mainly by lubrication to reduce the friction between adjacent lingoes. Several low viscosity oils were tried but the most successful material used was kerosene. This material was applied to the lingoes twice a shift and after its use was initiated, locking of face fabrics occurred only occasionally. One other modification that also helped was the shortening of about a third of the lingoes. This was done primarily to reduce the total load on the Jacquard heads and thus on the power train. However, it did provide these shortened lingoes with less surface for contacting adjacent lingoes.

- 4.5.7 Another problem encountered on the first parts woven was caused by the stiffness of the yarn imparted by the yarn finish. This wire-like property resulted in excessive and varying shuttle tension and was most evident at the left side of the loom where the filling yarn changed direction as it left the shuttle eye. The excessive tension would frequently tear out 20 to 30 warp ends at the left tab edge of the fabric and caused lengthy down time for redrawing these ends. Even when the warp yarns did not break, the force of the fill yarn was so great that it pulled some of the outermost warp yarns inward toward the adjacent warp yarns to form high density bundles while leaving a void of warp yarns where they should have been located. This problem was almost entirely eliminated by installing a crow hop as shown in Figures 19 and 25. It consists of a spring loaded sharp pointed finger activated by



4.5.7 Cont'd.

the reed, and drops down between two adjacent predetermined warp yarns as the reed of the loom moves to the rear. The outer warp yarns engaged by the finger bears the full tension of the fill yarn until the shuttle reaches the opposite side of the loom. As the reed moves forward, the finger is lifted out of the way and releases the fill yarn.

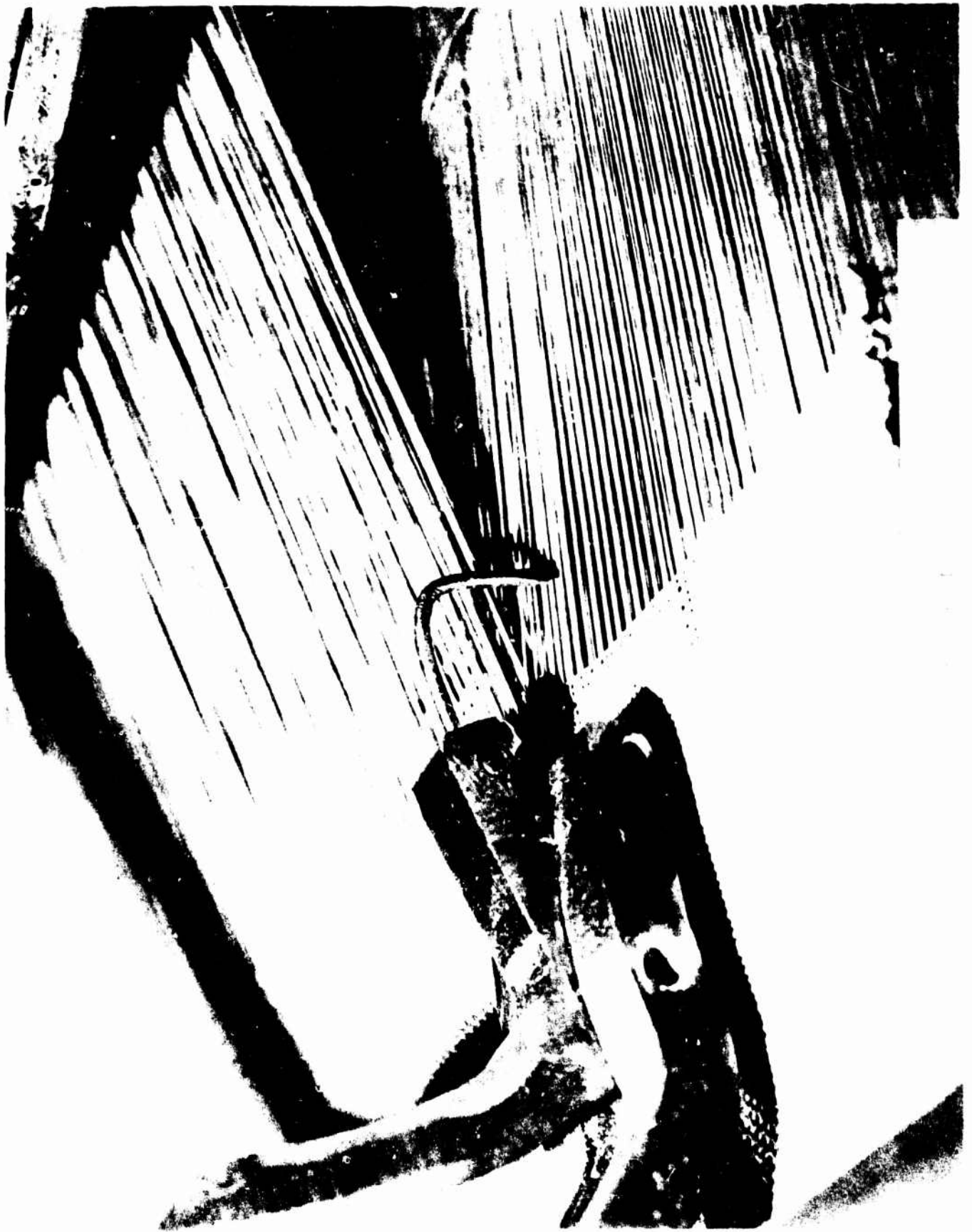
4.5.8 A similar problem occurred near the right edge of the fabric width, specifically at the edge of the outermost bottom lock. At those picks where the filling yarn looped around this edge, it pulled the warp yarn toward the center of the loom and thus created an open streak extending the length of the fabric similar to the type described in 4.5.7. A similar crow hop device was installed on the right side as shown in Figures 30 and 31 and the problem was solved.

4.5.9 As would be expected, weaving problems normally associated with conventional weaving were also encountered in this program, as for example, broken warp yarns, smashes, and mispicks. The major problems, however were caused by the vibrations in the fine adjustments of the timing elements in the system as previously discussed, and it became standard practice at the start of each shift to check and tighten all loom components that could have any bearing on the timing of the loom.

4.5.10 During the period that the timing adjustment problems were being solved, several modifications were tried in order to insure that the shuttles would make the full trip across the loom without being trapped in a closing shed. These included trying a heavily weighted shuttle and using waxed shuttles.



Figure 1. A View of the Right Side of the Machine



4.5.10 Cont'd.

It was found that no modifications were required, but it was during this weaving start up period that the hazard of flying shuttles became evident. Shuttles occasionally left their normal paths and flew as far as 30 to 50 feet with great force. While this sometimes occurs with all fly shuttle looms, the large mass of the shuttle of this loom made this condition especially dangerous. Heavy gauge metal guards were placed at each end of the loom and hinged guard covers were installed above most of the entire shuttle path between loom ends to protect the operators. A hinged guard cover is seen in Figure 27.

4.5.11 As discussed in paragraph 4.1.5 and shown in Figure 4, the float yarns from the locks on the inner face were cut by the operator during the weaving. This was necessary so that the two face fabrics would not lock together and prevent the layers from sliding over their respective draw rolls. To assure that the cut ends would not interfere with the subsequent coating operations, these yarns were trimmed very close to the surface of the inner fabric.

4.5.12 After the timing problem was solved and it was possible to keep the shuttle picking for extended periods, attempts were made to find the maximum amount of yarn that could be put on the shuttle bobbins. Because of the stiffness of the yarn as mentioned previously, this maximum amount of yarn corresponded to about 40 picks of weaving. Since the loom was not equipped with a shuttle bobbin magazine, extra shuttles with filled bobbins were prepared in advance and were quickly inserted in the shuttle box as soon as the previous unit was empty.

4.5.12 By the time the weaving phase was completed, fabric was being produced at the rate of about 1 lineal foot per hour. A view of the loom set up ready for weaving is shown in Figures 32 and 33.

4.6 Inspection and Inflation Procedures

4.6.1 The planned method of inspection was to inflate the fabric with customer-furnished bladders and check for contour. For this task, fixtures were made consisting of two metal frames fabricated from 2" x 2" x 1/4" angle iron, and from wooden blocks cut to conform to the computed shape of the fabric when inflated. These blocks were fastened to the inner faces of the frames, and screw eyes were inserted in the wood blocks. Each was to be used to position one end of the inflated fabric length and the two frames were to be anchored to the floor 20 feet apart, using bolts in pre-drilled holes fitted with anchoring shields. A sketch of this fixture is shown in Figure 34.

4.6.2 A manifold was constructed from lengths of 3/4" standard pipe and fittings and plastic hose so that a short length of hose coming from the main manifold was available to be attached to each of the 12 bladders. Special connectors had to be machined to permit attaching the hose to the valves that had been incorporated in the bladders. Air was fed to the manifold through a line equipped with a pressure regulator, pressure gage, a 2 PSI relief valve and suitable shut off valves.

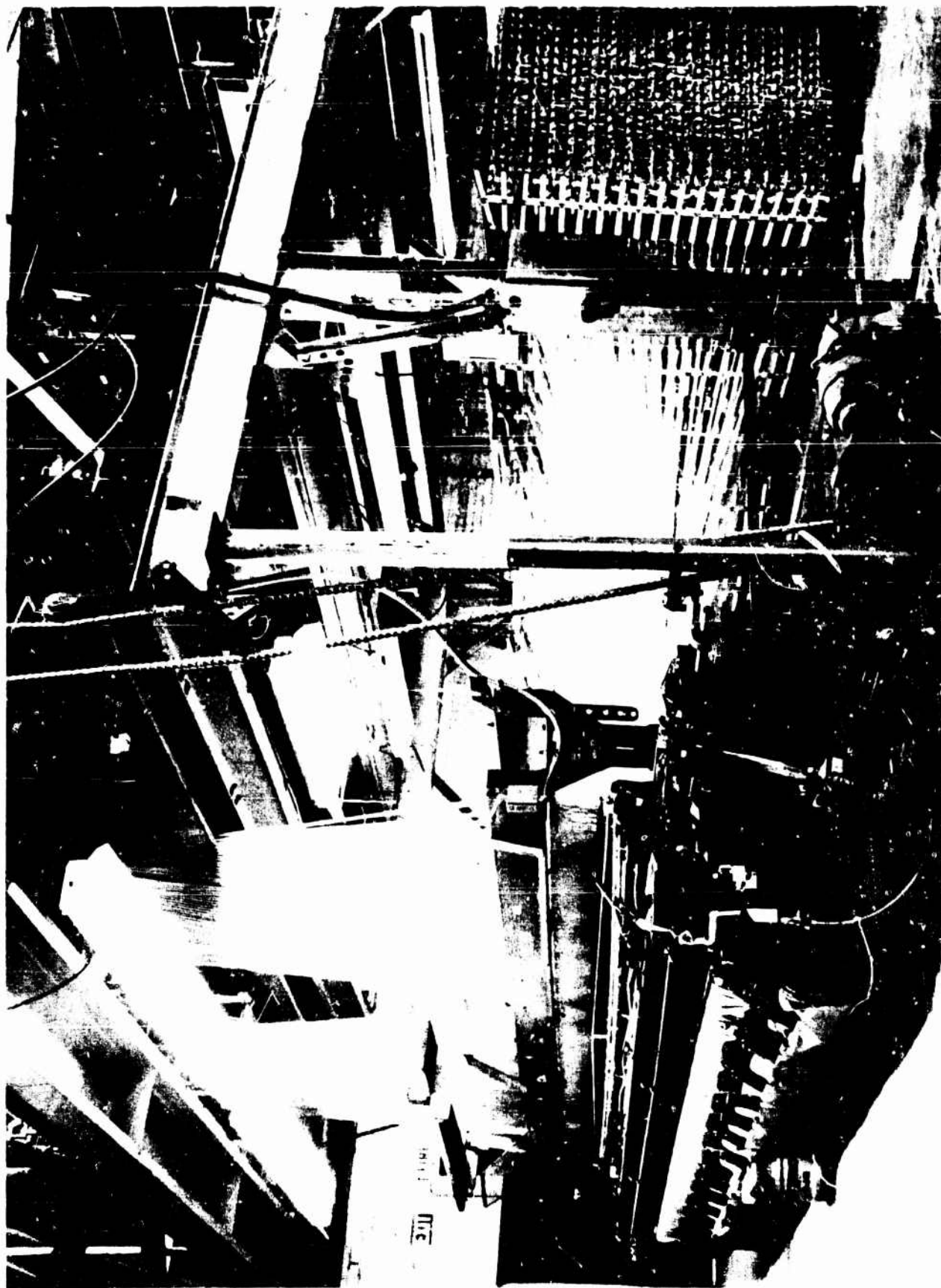
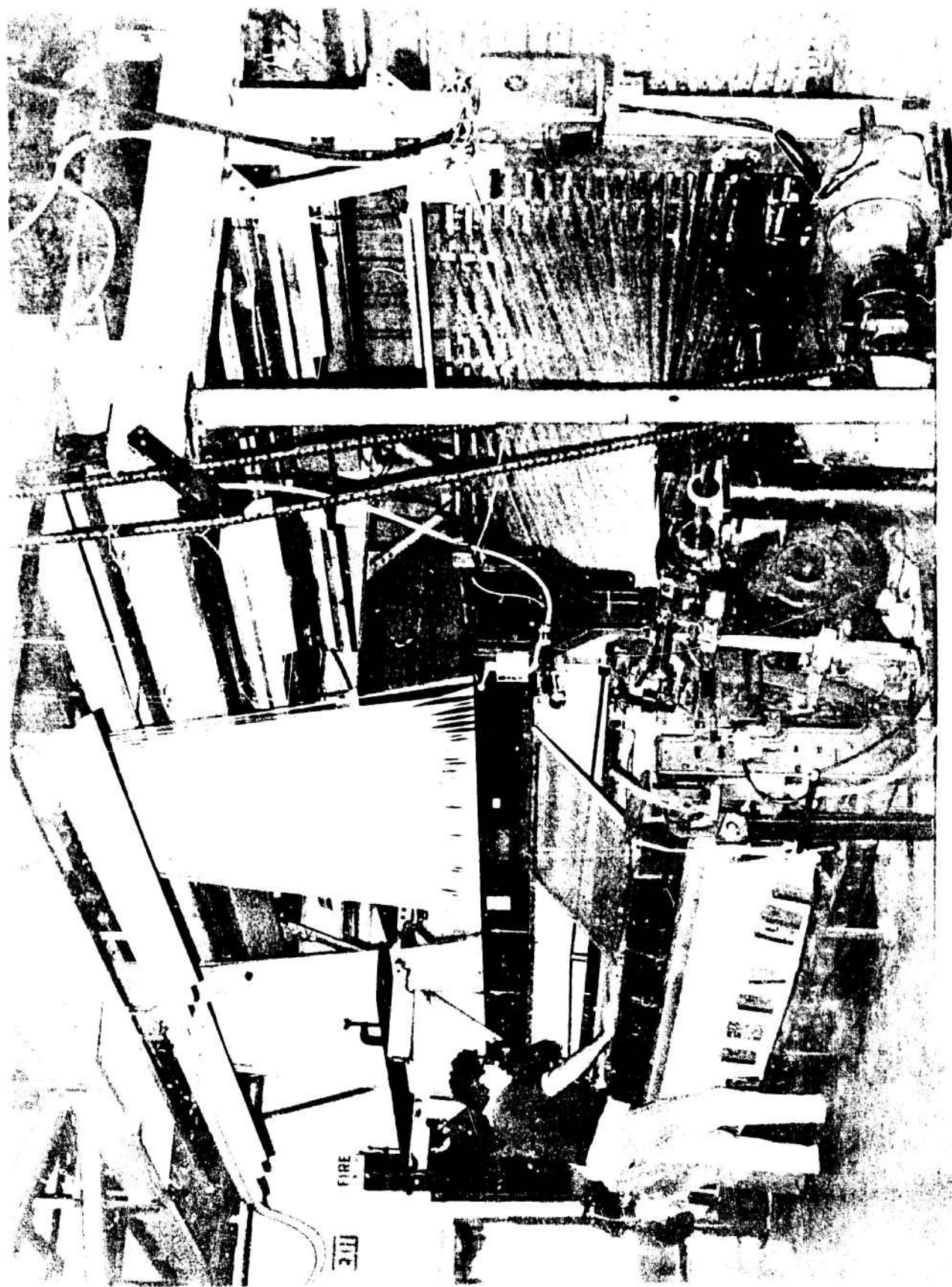


Figure 42 View of Comp. Life Loom Set Up Ready for Weaving



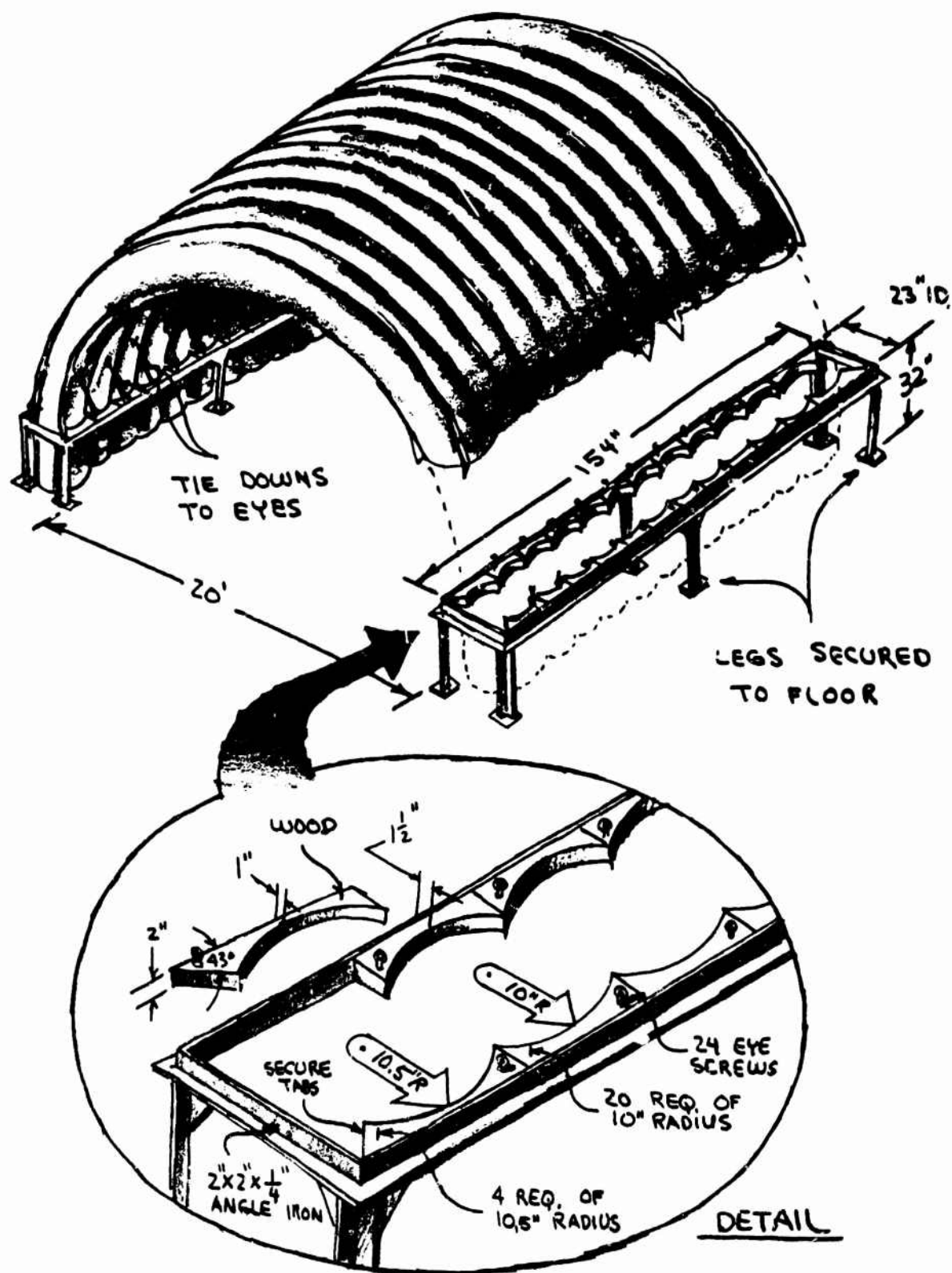


Figure 34 - Frame Fixture for Restraining Inflated Fabric

- 4.6.3 Prior to inflating a part, the fabric was laid on the floor and unrolled with the inner face down. Since the cell sizes were large enough, an operator was able to traverse the interior length of each cell to inspect the ribs and to cut apart any fabric faces that had been locked together by problems previously discussed. As the operator passed through the cells, he trailed behind him a length of twine which was allowed to project at each end of the fabric. One end of the twine was tied to a 1/4" diameter rope which in turn was attached to an uninflated bladder. Each bladder was pulled through a cell, making sure that the inner surface of the bladder was against the inner surface of face fabric. While one person pulled the bladder through, another held the opposite end of the fabric to facilitate this operation. All 12 bladders were inserted this way and the bladder ends aligned as closely as possible by eye. When connected to the manifold in this condition and air introduced, the start of inflation would have the inner face of the fabric essentially flat and the outer face, which was about five feet longer, wrinkled. As the bladders were inflating, they would expand to their full diameter before the fabric assumed its semicircular inflated shape, and friction between the bladder and outer fabric face resulted in considerable wrinkles in the outer face. This pointed up the fact that some work was necessary to learn how to inflate with a minimum amount of wrinkles.
- 4.6.4 Several methods were tried to minimize the wrinkles. One was to close the ends of the fabric by hand sewing all the cell ends prior to inflating with the hope that the bladders would

4.6.4 Cont'd.

push against these closed cell ends and develop force in the long dimension of the cells. See Figure 35 and 36. This was effective in relieving the wrinkling condition somewhat, but the hand stitched closures failed when the sewing yarn broke before full inflation was completed. Generally, however, regardless of which method tried, it was found that multiple inflations with manual pulling of the fabric over bladders between inflations appeared to be very effective.

4.6.5 The bladders furnished were not fabricated to a true circular arc but were made up of a series of chords. While this did not pose a serious problem for inflating the fabric, it resulted in some inevitable wrinkling of the fabric particularly at the areas where the chords intersected. Also, no exact control was possible over the lengthwise or vertical position of the bladders when inflated without the use of restraints. Figures 37 and 38 show this condition in the inflated bladder. Figure 39 shows the first partial fabric length that was inflated. The "wildness" of the unsupported lengths of bladders in this test indicated the need for using full fabric length in subsequent inflation tests. Some of the excessive wrinkling including that caused by the chords can be seen in this photo.

4.6.6 The inflation procedure finally adopted for the full size fabric lengths was as follows:

- (1) Unroll the fabric on the floor with the inner face down.
- (2) Pull the inner face as tight as possible.
- (3) Pull the uninflated bladders through each cell, one at a time.



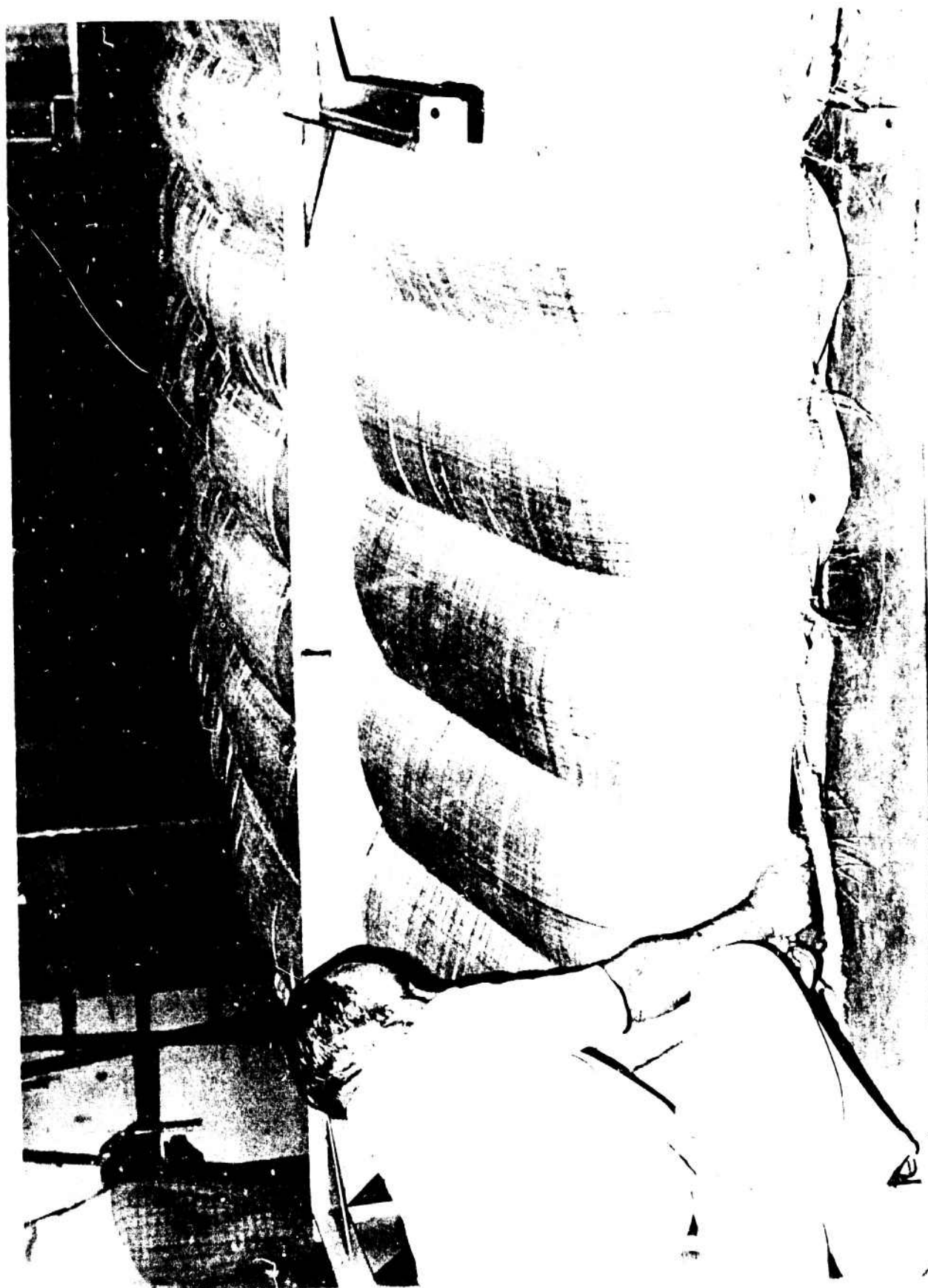


Fig. 20. Closing Cell Folds on opposite Side by Hand Stitching.
[The figure is a detail of the work shown in Fig. 19.]





Figure 38 - Close Up of Inflated Bladders

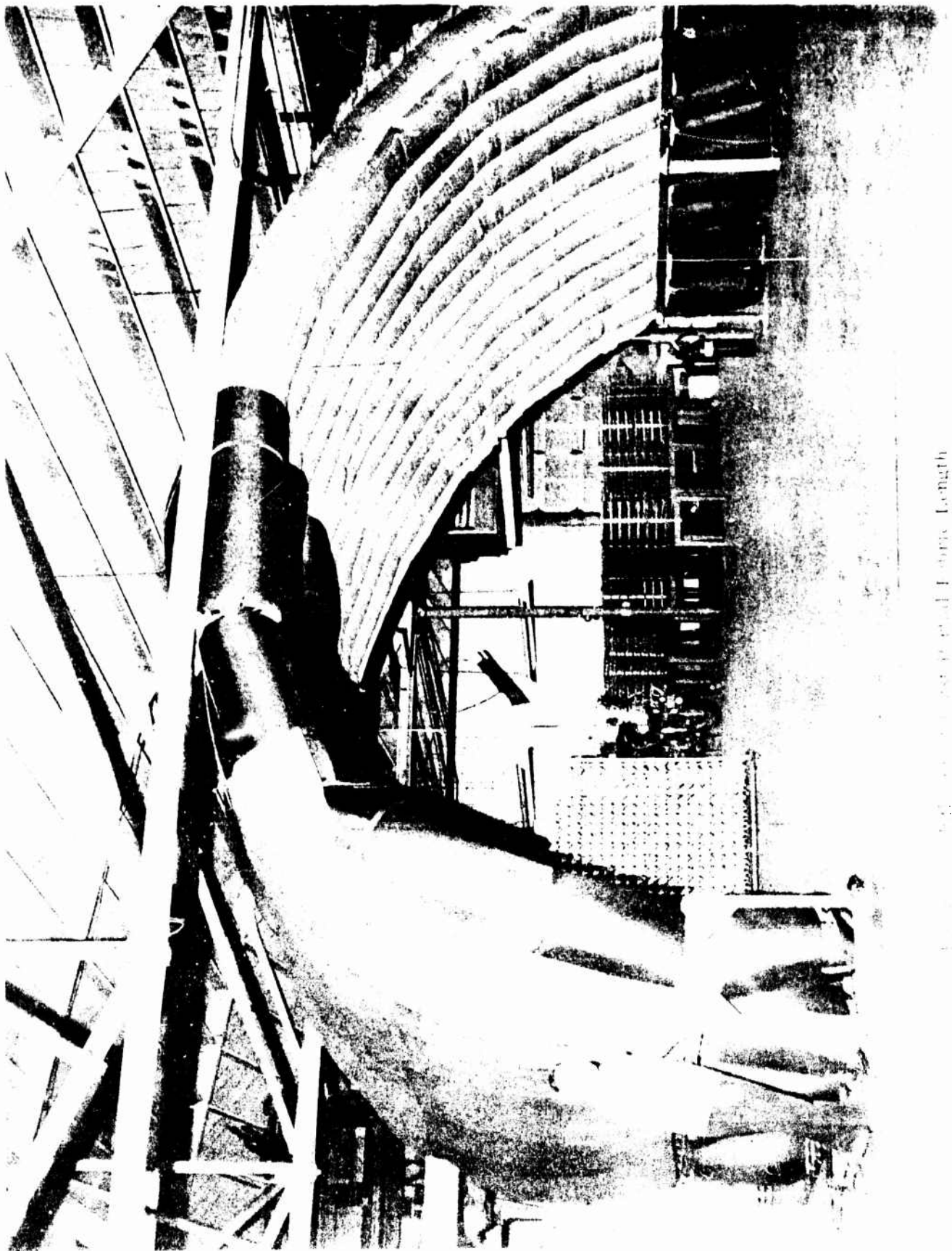


Fig. 1. View of the hull of the ship "Length"

4.6.6 Cont'd.

- (4) Stretch the inner face until relatively free of wrinkles.
- (5) Mark an indexing line 3 ft. from one end of the inner fabric and extending across the width of the fabric (3' is the height of the fixture). Put a second indexing line 31' 5" as measured along the inner face from the first line. Follow the respective picks from the inner face indexing lines to the outer faces and mark the corresponding outer face index lines.
- (6) Set the ends of fabric into the restraining fixtures so that the indexing marks are even with the tops of each fixture.
- (7) Attach tie-down cords to all the locking areas of the inner and outer fabrics. These attachments should be 18 inches inward from the fabric indexing marks. Tie the other ends of the cords of the inner fabric to the tops of the respective restraining fixtures so that the cord lengths are all approximately 18 inches. Do not tie the cords from the outer fabric to the frame.
- (8) Tip the restraining fixture at the manifold end of the fabric to its vertical position and bolt the frame to the floor.
- (9) Inflate the fabric to 1-1/2 psi. While inflating, move the remote restraining fixture inward. When the part is about half inflated, tip the restraining fixture to its vertical position, move it inward to its final location and bolt the frame to the floor.

4.6.6 Cont'd.

- (10) Partially deflate to about 1/2 psi. Tie the outside fabric tie down cords to the top of their respective restraining fixtures so that the cord lengths are about 18 inches. Reinflate to 1 1/2 psi.
- (11) Partially deflate to about 1/2 psi. Tighten the cords on the inner and outer fabrics and reinflate.
- (12) Repeat step (11) two more times or until wrinkles in structure are at a minimum.

Figures 40, 41 and 42 are photographs of a part inflated by this procedure. The cords on the inner face were removed from this part but the outer face cords are still in place. It can be seen that both faces are relatively wrinkle free.

- 4.6.7 Fabric inspected for major defects after removal from the loom and prior to the inflating. Uninflated dimensions were taken at this point. After inflating, other previously unobserved major defects were noted, and inflated dimensions taken. Major defects as observed were repaired prior to and after having been inflated.

4.7 Defects and Repairs

- 4.7.1 Several typical fabric defects were encountered each of which required a special type of correction or repair procedure. One type was observed sometimes during weaving when floating fill yarns on the inner surface were being trimmed. This type would occur where the float yarns passed through the fabric surface causing the adjacent warp yarns to separate and was caused by the shape of the shed. These conditions were usually repaired while on the loom although sometimes they were repaired

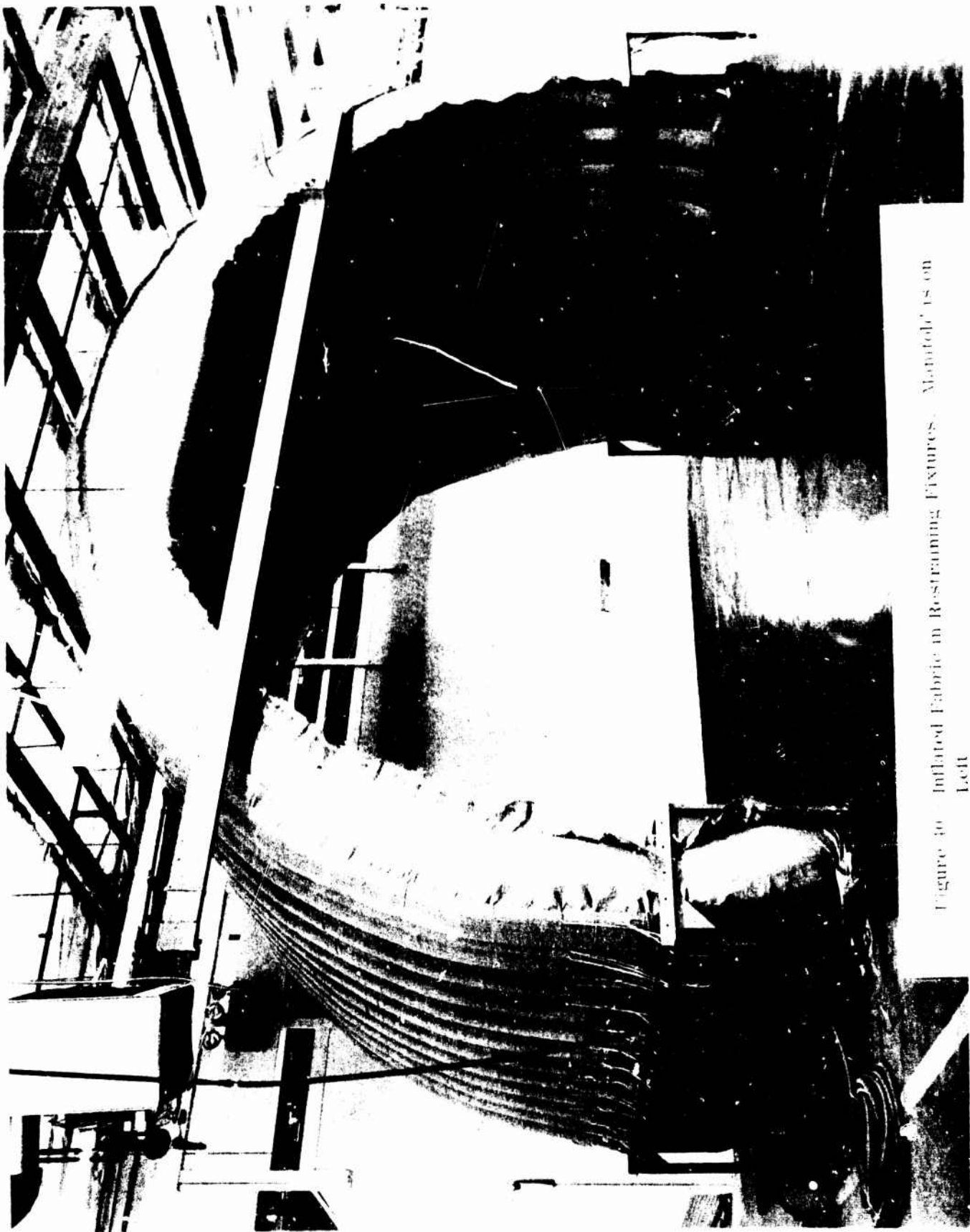


Figure 40 Inflated Fabric in Restraining Fixtures. Mandrel is on Left

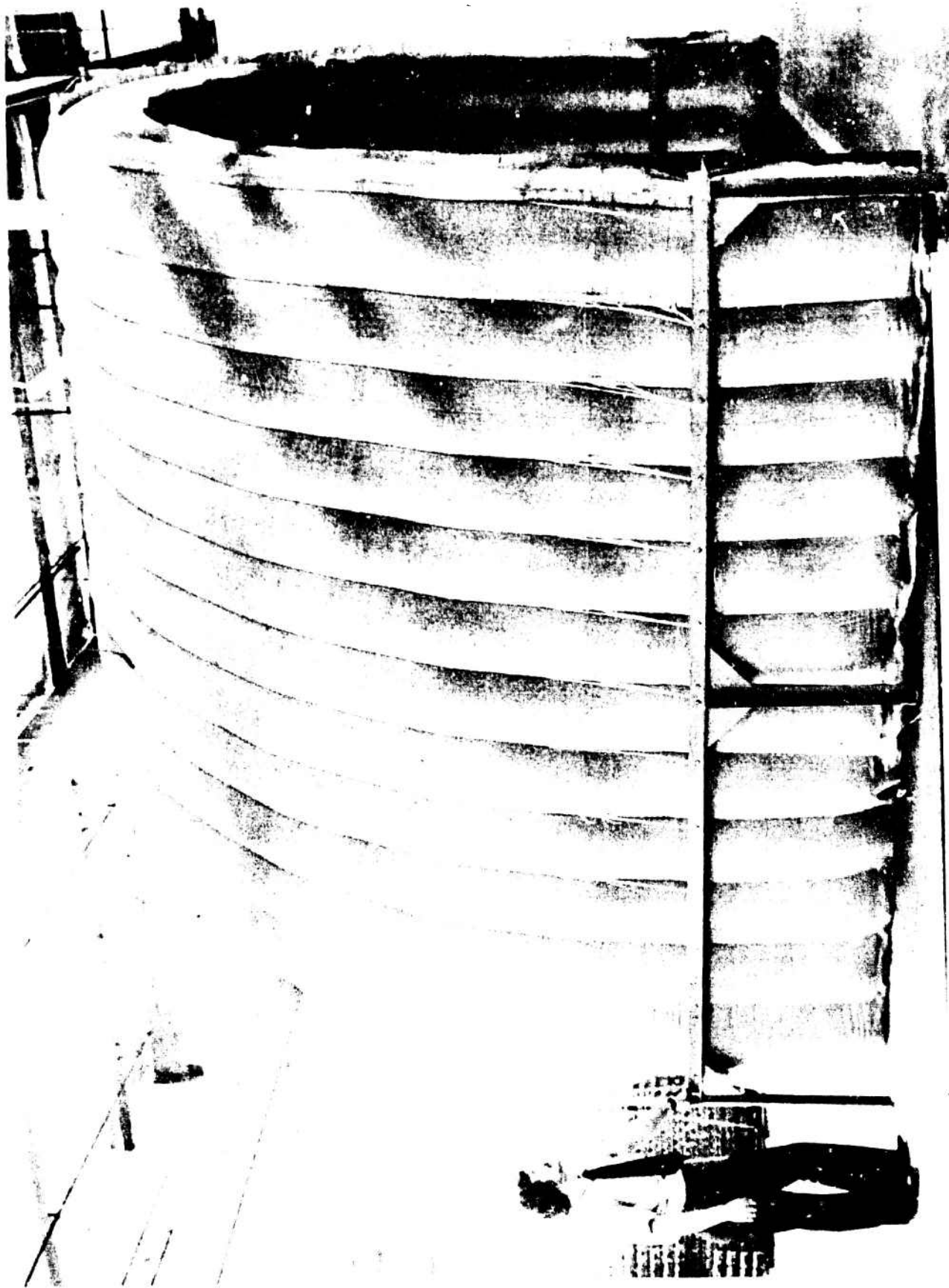


Figure 11 - Outside Face of Inflated Fabric

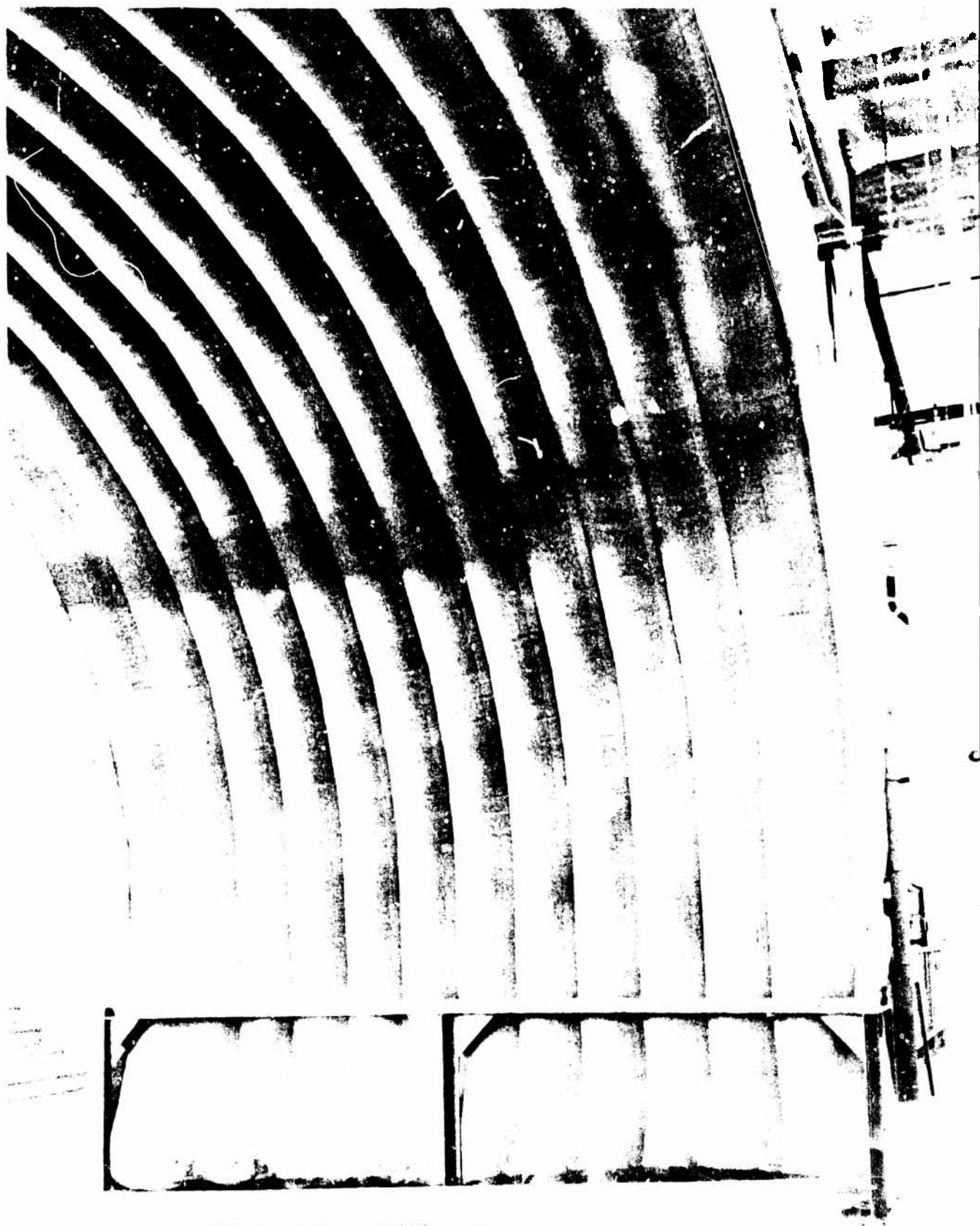


Figure 12 - Inside of the 1911 car

4.7.1 Cont'd.

later after removal from the loom. In this condition all the required warp yarns were present but improperly spaced. Repairing consisted simply of using a needle to slide the mislocated warp yarns to their proper position. A typical shed opening that contributed to this condition is seen in Figure 28. Figure 43 illustrates this type of defect.

4.7.2 Figure 44 shows a defect of a missing warp yarn caused by the warp yarn being broken. Similar appearing defects were caused by missing picks or fill yarns. In a plain weave fabric such as this, the appearance of this defect is that of parallel adjacent yarns acting in pairs as though they were part of a basket weave. These were repaired off the loom by using a needle and manually inserting a new warp or fill yarn over and under the appropriate yarns, keeping the needle between the parallel yarns. Most of the defects in the warp direction occurred in the outer face because of the problem of not being able to see this face as it was being woven. Broken warp yarns affecting the inner face could be taken care of on the loom as they were observed.

4.7.3 When malfunctioning Jacquard hooks would cause two fabric layers to be woven together, these layers literally had to be cut apart resulting in fabric having defects with the appearance of tears. Similar appearing defects were sometimes caused by shuttle smashes. These defects were repaired by darning using the same 840-denier yarn as used in weaving. Figure 45 shows one of these defects being repaired.

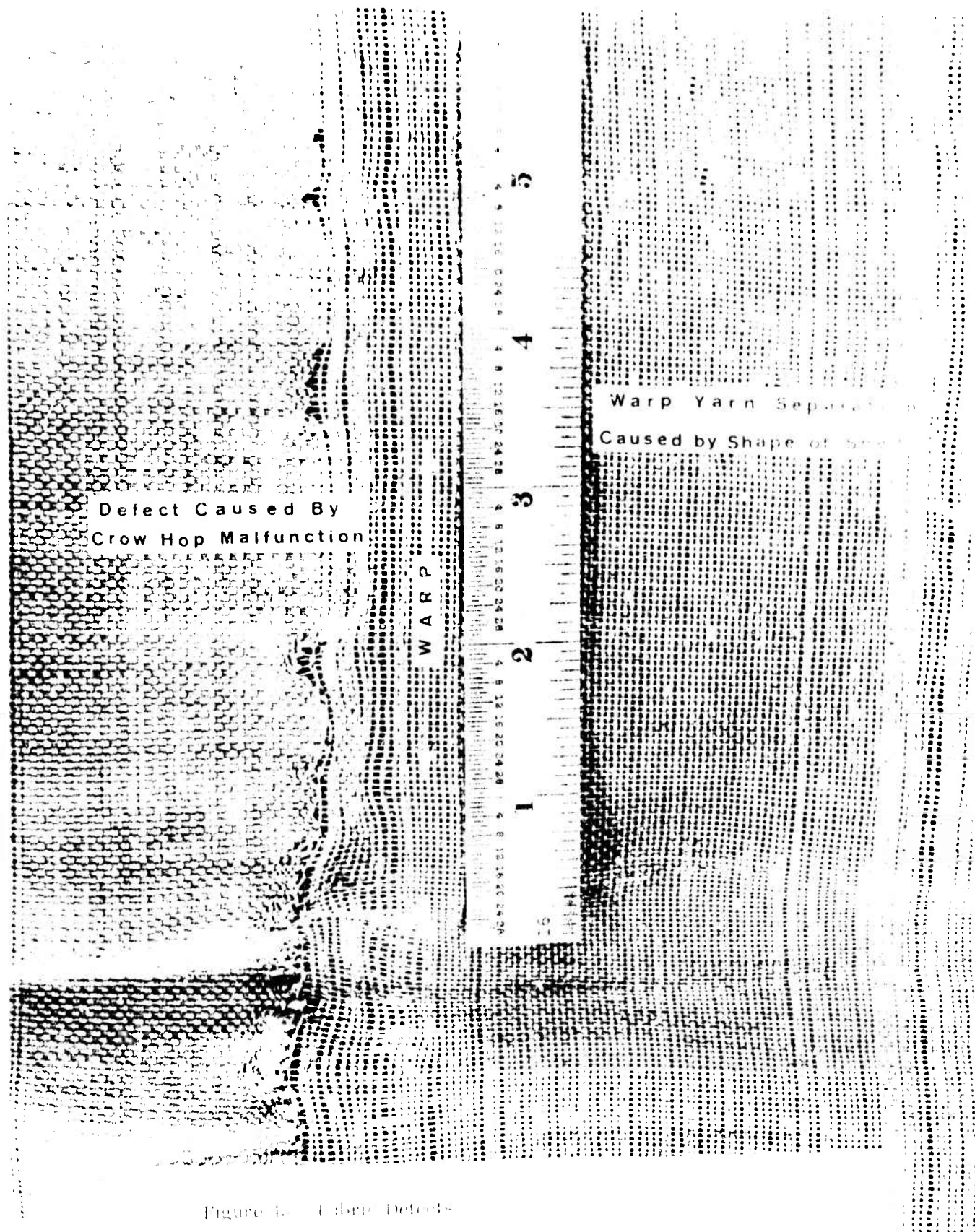
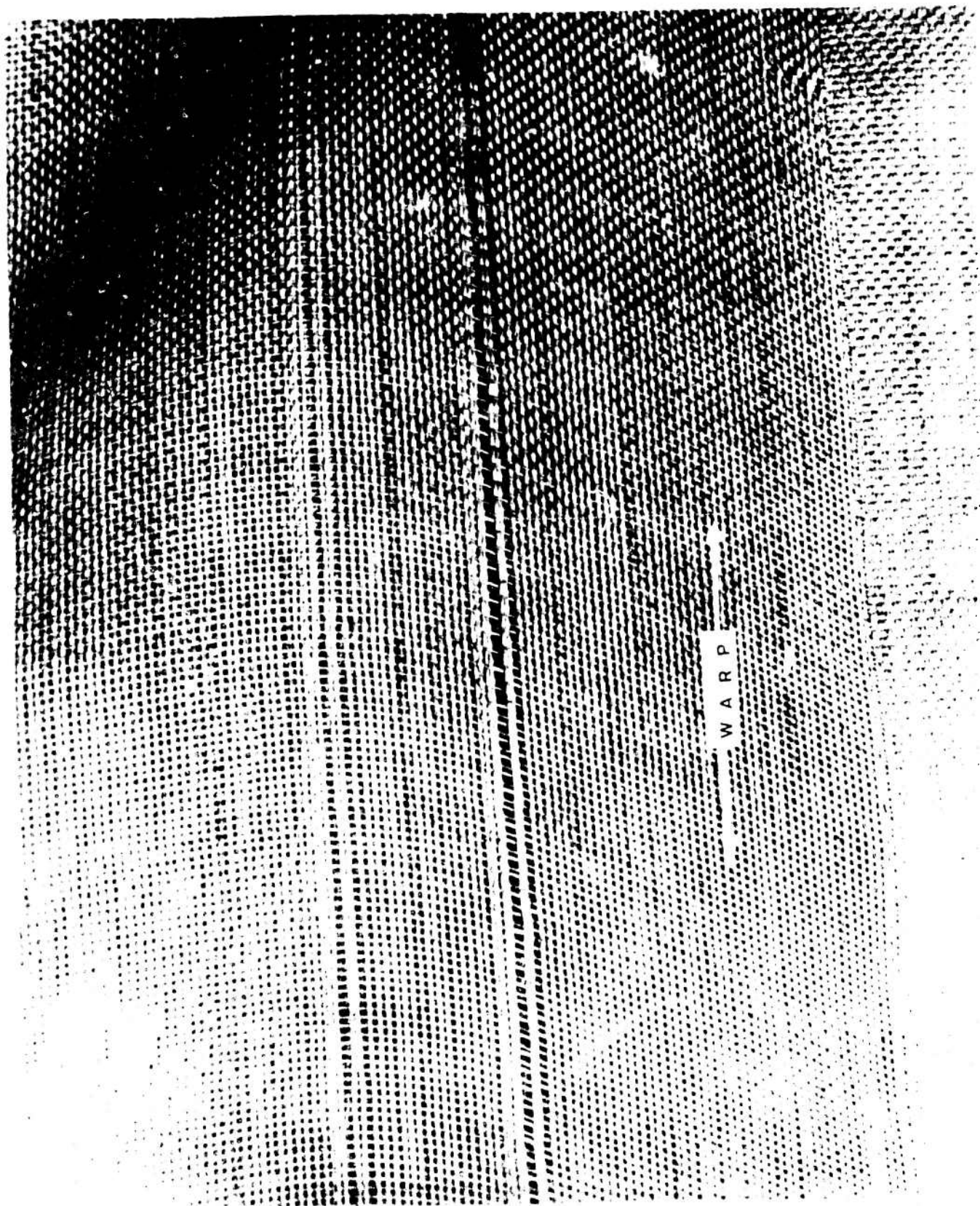


Figure 1. Fabric Defects



W A R P

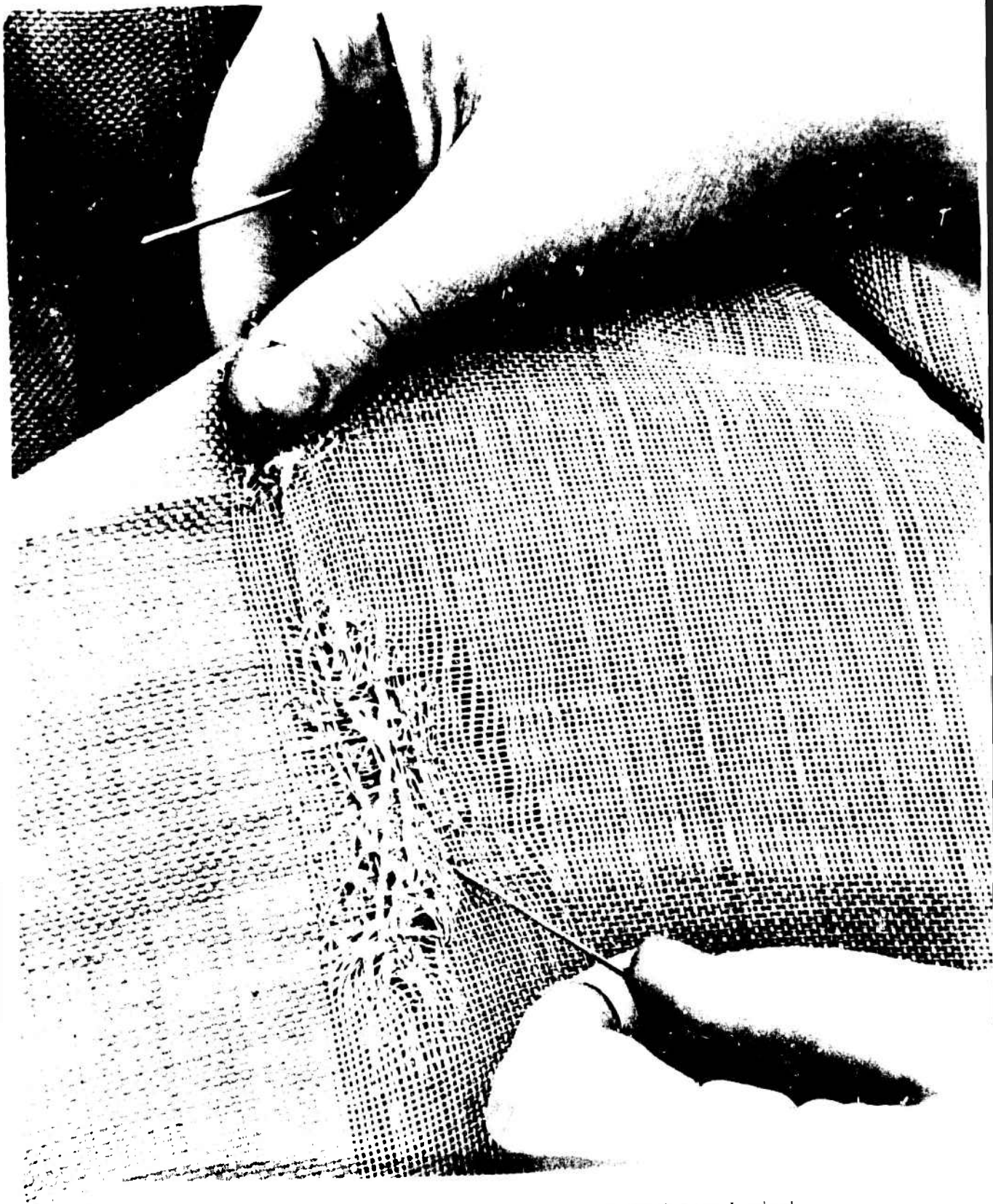


Figure 1. Repairing Cut Fabric Where Faces Had Been Locked Together

4.7.4 Figure 46 shows the defect described in paragraph 4.5.7 which was eventually minimized by the use of crow hops. These voids in the warp direction were beyond the inflatable portion of the fabric and therefore it was felt that they would not pose a serious problem in coating. The warp yarns that had been pulled inward were so tightly locked to the adjacent yarns that it was impossible to separate the yarns as was done for correcting the defect described in paragraph 4.7.1. Most of the fabric in the three parts shipped had very little of this defect because of the effect of the crow hops. However, there were periods when the devices were not working properly because of bent wires in the crow hops, and the void area defects took on the appearance seen in Figure 43. Figure 47 shows a crew of operators repairing fabric. Considerable time was spent in this operation but all parts shipped were in a condition suitable for coating.

4.8 Fabric Data

4.8.1 Because of the time expended in solving the previously discussed problems, a deadline was rapidly approaching that required that the premises housing this program be vacated. To meet this deadline a contractual change was made to reduce the required quantities of fabric, and per this change, one five-yard length and three forty-yard lengths were produced and delivered. The five-yard length was repaired and inflated, but the inflated dimensions were not too meaningful because of the previously discussed problem concerning the unsupported length of bladders. Nevertheless, this part indicated that the target dimensions were reasonably close to being attained.

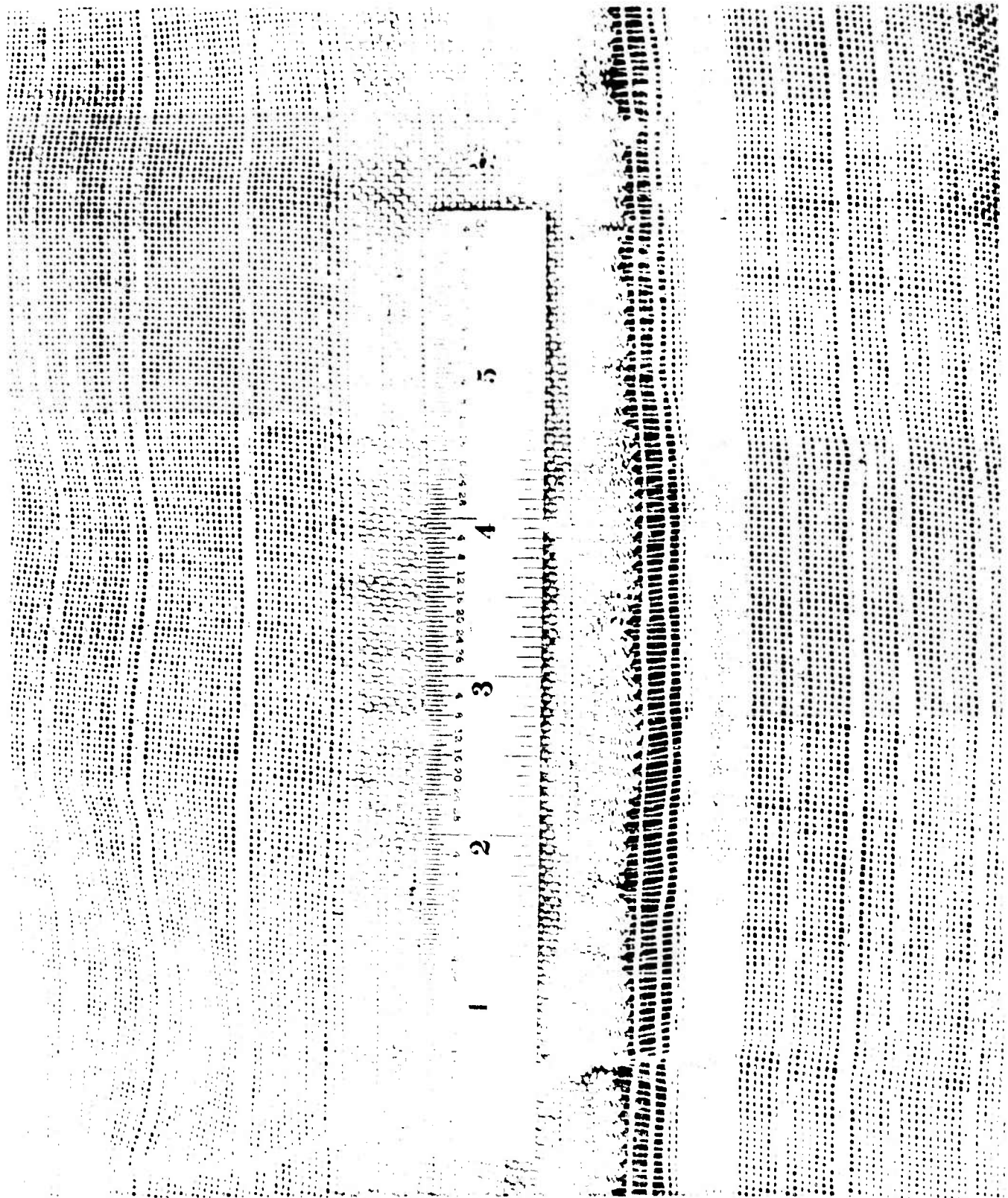


Figure 35 - Defect Caused by Tensioned Fill Yarn Dragging Warp Yarns Out of Position



4.8.2 The three full length parts were inspected and the following data obtained: (Dimensions given are average values on uninflated fabric).

	<u>Part 1</u>	<u>Part 2</u>	<u>Part 3</u>
Length of Part (measured along inner face)	39' 0"	37' 10"	38' 9"
Weight of Part	91 lb	88.5 lb	89.5 lb
Fabric Width, Not Including Tabs	162"	161"	161"
Cell Height	16"	15 3/4"	15 3/4"
Center Cell Width, Measured at Outer Face	13"	13"	13"
Center Cell Width, Measured at Inner Face	13"	13"	13"
End Cell Width, Measured at Outer Face	16"	15 3/4"	16"
End Cell Width, Measured at Inner Face	16"	15 3/4"	15 3/4"
Warp & Fill Count, Outer Face	22 1/2 x 22 1/2	22 x 22 1/2	22 1/2 x 22 1/2
Warp & Fill Count, Inner Face	23 x 27	22 1/2 x 27	22 1/2 x 27
Warp & Fill Count, Lock Area, Inner Face	45 x 53	44 x 53	42 x 53
Warp & Fill Count, Lock Area, Outer Face	44 x 44	44 x 44	44 x 44

4.8.3 The inflated fabrics as held in the restraining frames were checked for contour. The height of the inside of each arch from the floor for all three parts was within 2 inches of 13 feet. Since the tops of the frames were 3 feet above the floor, this means that the inside radius of the parts were 10 feet $\pm$ 2 inches, fairly close to target. The fabric

4.8.3 Cont'd.

width measured at the frames was 154 inches since this was the dimension of the wood restraint insert of the frame.

Above and below this restraint the fabric appeared to expand an additional 1 to 2 inches.

- 4.8.4 While the fabric lengths produced had a sizable number of defects and required much repair work, there was no question that the program objective had been achieved. Complete woven inflatable modules close to target requirements were made.

5.0 DISCUSSION AND RECOMMENDATIONS

From the experience gained during the course of this contract, several problem areas are worthy of further consideration from both technical as well as economical aspects.

- 5.1 The number and type of weaving problems and defects encountered were analyzed on a qualitative basis, and it appeared that about three fourths of these resulted from using a Jacquard system of programming. This includes the directly related problem of the crowded lingoes which resulted in the tendency of the fabric plies locking together. The balance of the problems arose mostly from the picking mechanism adjustment difficulties and to a minor degree, from the characteristics of the finished yarn.

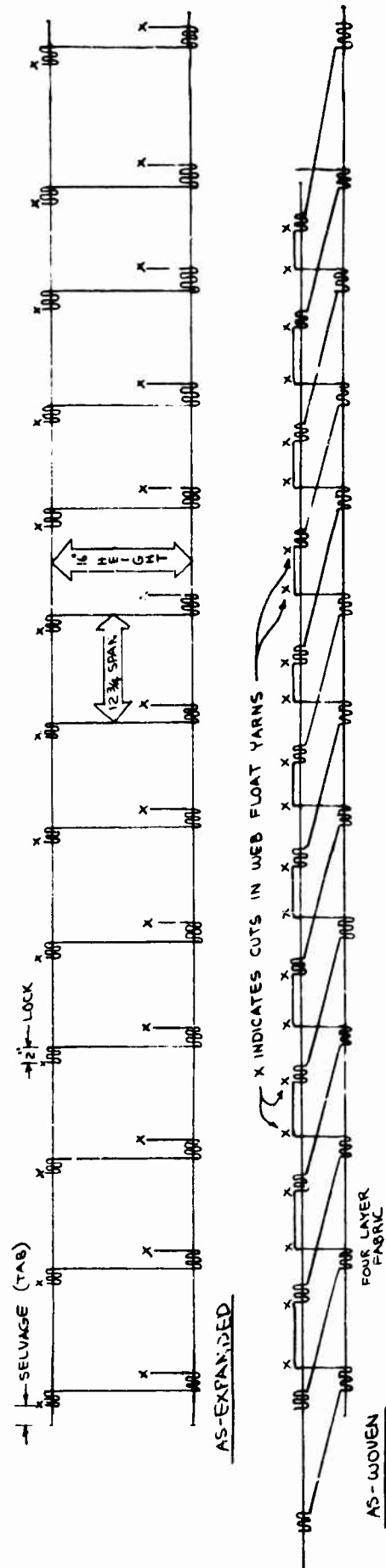
- 5.1.1 As previously discussed, the finish on the 840 denier Dacron yarn created problems in weaving, particularly in the shuttle operation. It would appear that some investigation should be made in finding or developing a finish suitable for weaving and compatible with the coating used. Ideally, this finish would allow the yarn to retain its natural flexibility rather than impart the high degree of stiffness experienced in this

5.1.1 Cont'd.

contract effort. Since the prime function of the fabric is to contain the pressurized bladders, it may very well be that the adhesion of coating to fabric may not have to be the maximum attainable.

5.1.2 Future weaving of this type of product should not use a Jacquard system but should be based on using harness frames controlled by a dobby or other similar type of head motion. While this was not possible for the loom available in this program, and although fabric having target requirements was successfully made, it is now strongly believed that for production, a basic harness setup on a suitable type of loom must be used. The types of looms considered for production are discussed later in this report.

5.1.3 The fabric design used in this program was based on the current cell dimensions of the MUST shelter module as shown in Figures 2 and 4. In the collapsed condition, as it is when weaving, the main body of the fabric in reality consists of four layers of material. (The lock area is two layers, the web and the opposite face each is one layer). These four layers result from having the cell height (16") greater than the web spacing (12 3/4"). This is further illustrated in the top two sketches of Figure 48. The lower two sketches of Figure 48 show a proposed fabric configuration in which the web spacing (21") exceeds the cell height (16") by 5". In the collapsed condition, it can be seen that there are now three layers of fabric to be woven rather than four. This 5" excess of span over cell height would allow for 2" locks plus 1" for



CURRENT WOVEN CONCEPT

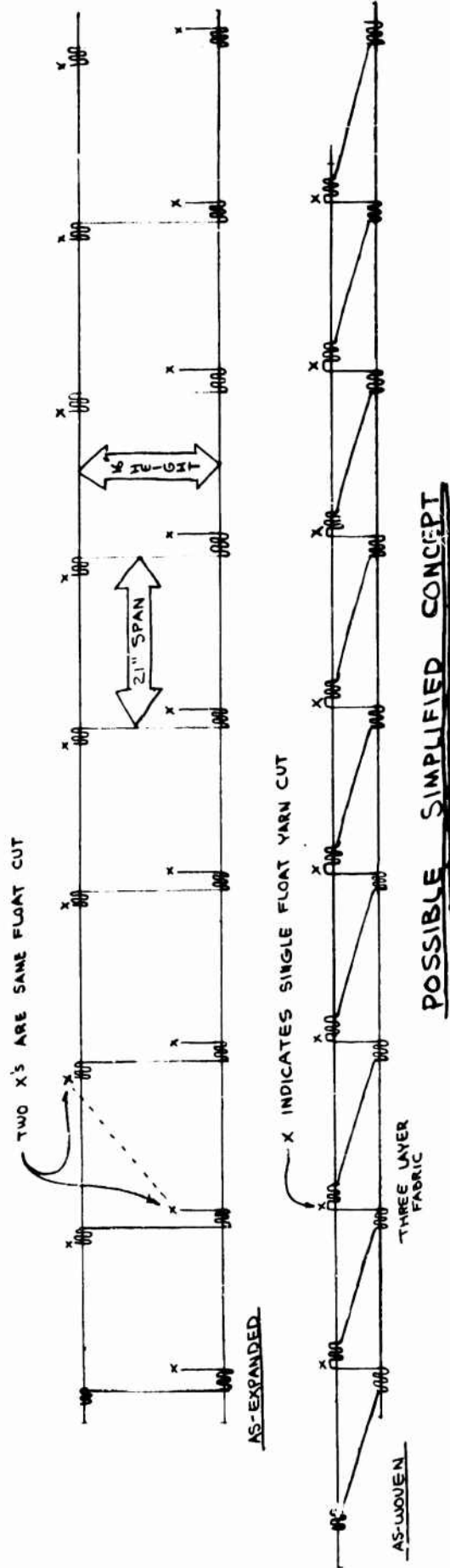


Figure 48 - Comparison of Current & Possible Simplified Fabric Designs

5.1.3 Cont'd.

trimming float yarns. Such a change would permit a 25% increase in the production rate since there would be six picks per repeat rather than eight as was required for the present design. This also would reduce the number of harness frames required by two and would somewhat reduce yarn waste because of the shorter length of float yarns to be cut off.

- 5.1.4 Such a change, where the distance between webs equals the height plus 5 inches, would alter the shape of the inflated cells and might not be compatible with the existing bladder design. It might also introduce additional distortion or wrinkles in the fabric because the draw rolls, as they were for the current effort, are pulling equal length warp yarns across the width of each face fabric regardless of whether the warp yarns are in a lock or are midway between two adjacent locks. Upon inflating, the warp yarns centrally located between adjacent locks want to be longer than those closer to the locks, and since they cannot, (except for a slight yarn stretching), the fabric compensates for these different lengths by developing wrinkles close to the lock areas. Although this condition would normally be expected, the parts produced in this program had a minimum amount of wrinkling in this area. However, the greater the difference between the web spacing and height, the greater will be the wrinkling. This could be overcome to a great degree by using scalloped draw rolls as shown in Figure 49. As can be seen, the larger diameter sections of the rolls will cause the fabric lengths

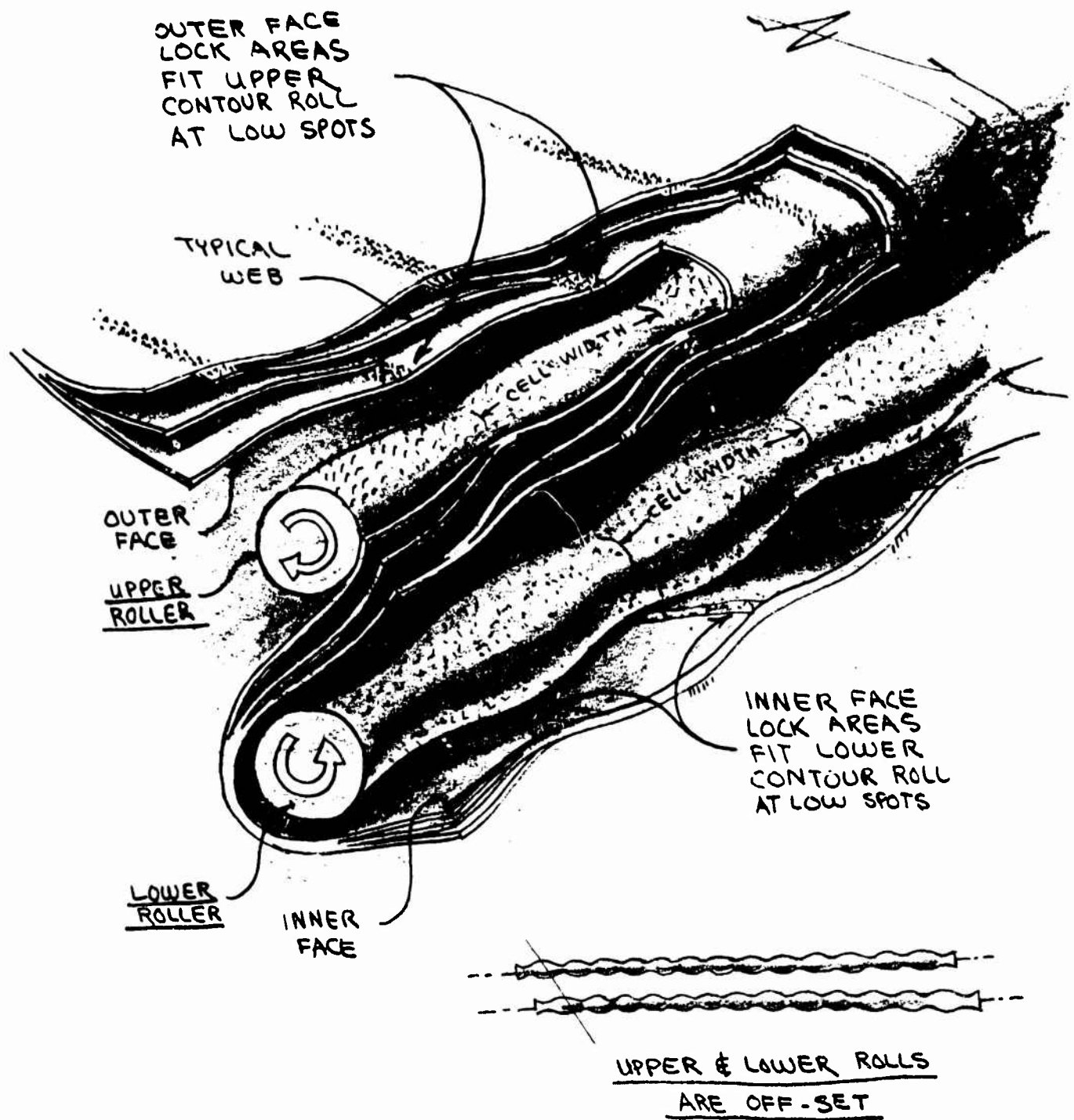


Figure 49 - Draw Roll Design to Minimize Wrinkles

5.1.4 Cont'd.

to be longer than the smaller diameter sections that correspond to the locks. Fabric produced this way will appear to be distorted when removed from the loom since it will be impossible to stretch either face to a flat condition because of the different length of warp yarns within each face. However, since there could be potential savings, a consideration should be given to fabric having a wider web spacing than height.

5.1.5 Considerable thought has been given to the type of production weaving equipment best suited to producing the shelter fabric. The basic essential requirements for such equipment includes the following:

- (1) Reed width of at least 192"
- (2) 20 harness capacity
- (3) Sufficient space and heft for the following modifications:
 - a) Equipping with two draw rolls, friction roll and wind up roll.
 - b) Equipping with large power drive.
 - c) Adapting to run with combination of warp beams and creels.

5.1.6 The following three types of looms were considered for production weaving:

- (1) Fly shuttle loom with harness motion.
- (2) Felt loom
- (3) Shuttleless loom

The 192" Draper loom of the type used is at or near the limit of width at which it would be feasible to operate. It would be possible to further modify this type of loom by fabricating

5.1.6 Cont'd.

entirely new loom sides and repositioning the crankshaft so as to make possible the use of harnesses. This modification would have to include a new take up mechanism and the addition of new dobbies. About all that could be salvaged from the original loom or from a new fly shuttle loom of this general type would be the picking motion and box parts. Such a rebuilt loom would still be limited to about 66 picks per minute and even with an automatic bobbin change unit, it is doubtful that an efficiency of over 60% could be maintained. With the present fabric design, this would result in a production rate of approximately 2 lineal feet per hour.

5.1.7 Felt looms are extremely heavy looms primarily used for weaving papermaking felts up to 50 feet wide. These looms were manufactured up to about 15 to 20 years ago in the United States by Crompton and Knowles who discontinued production with the advent of non-woven felts, now the major type of paper-making felt used. While it may be possible to obtain this type of equipment overseas, it is believed that the equipment and parts availability might be a major problem. The big advantage of this type of loom is its massive ruggedness and its lack of timing problems. The yarn shed can be kept opened as long as desired to allow the shuttle to pass through. These are slow operating looms and run about 20 to 24 picks per minute which would probably produce fabric at about 0.7 feet per hour. For fabrics wider than that produced on the present program, this loom may be the only type to be considered. For example, a felt loom could be modified and used to weave

5.1.7 Cont'd.

inflatable fabric 2, 3, or even 4 modules wide, or in other words, a full MUST shelter. Whether the wider fabric would be practical from an overall weaving, coating, fabricating and deployment point of view, or from economical or other considerations was not investigated, but the idea of this possibility is intriguing.

5.1.8 Several shuttleless types of looms are in use or under development. The type that appears to be adaptable to producing the fabric module to the MUST design is the Sulzer loom made in Europe and widely used in the United States for production weaving of wide fabrics. This loom is a strong heavy duty machine and appears to be capable of accommodating the modifications that are necessary. The fill yarn is introduced into the fabric by a projectile which takes the yarn from a package at the feeder side of the loom and travels through a cage formed within the shed opening across the fabric width. The fill yarn is cut and the projectile drops into a conveyor under the loom heading back to the feeder. Meanwhile, additional projectiles perform the same operation in rapid succession. With loom speeds up to 120 to 150 picks per minute and efficiencies of 80%, it may be possible to attain weaving rates approaching 5 lineal feet per hour. The fabric coming off a shuttleless loom does not have a selvage which might be a consideration depending upon how the fabric is to be coated. If this is a problem, the raw edges could be protected by sewing or otherwise attaching fabric strips to the edges. This type of loom should be able to handle the stiff-finished fill yarn better than fly shuttle looms. Of all the loom systems considered, the Sulzer

5.1.8 Cont'd.

shuttleless loom appears to be the choice for weaving production quantities of the present fabric module design.

5.1.9 Regardless of which type of loom is considered, it appears that two warp beams should be used, one for each of the face fabrics since each of these would have its own fixed length. The web warp would be supplied from creels because of the varying warp lengths. Of course if scalloped take up rolls are used as discussed earlier, the complete warp system would have to be set up on creels since most warp yarns would be travelling at different rates.

5.1.10 The scope of this program did not include a complete characterization of the fabric produced. Such a characterization study would be necessary for formulating a purchasing specification for the woven fabric. However, the following items might be incorporated into a preliminary specification based on the work done on this program:

Yarn

- | | |
|---------------------------------|-----------------------|
| (1) Type - 840 denier polyester | 2.5 TPI, Heat Treated |
| (2) Finish | RFL Treated |

Outer Face Fabric (Between Locks)

- | | |
|----------------------------|------------|
| (1) Type Weave | Plain |
| (2) Warp Count (Ends/In.) | 22 $\pm$ 2 |
| (3) Fill Count (Picks/In.) | 22 $\pm$ 2 |

Inner Face Fabric (Between Locks)

- | | |
|----------------------------|------------|
| (1) Type Weave | Plain |
| (2) Warp Count (Ends/In.) | 22 $\pm$ 2 |
| (3) Fill Count (Picks/In.) | 26 $\pm$ 2 |

5.1.10 Cont'd.

Outer Face Fabric (Locks)

(1) Type Weave	basket
(2) Warp Count (Ends/In.)	42 $\pm$ 3
(3) Fill Count (Picks/In.)	42 $\pm$ 3
(4) Width of Lock	2" $\pm$ 1/8"

Inner Face Fabric (Locks)

(1) Type Weave	Basket
(2) Warp Count (Ends/In.)	42 $\pm$ 3
(3) Fill Count (Picks/In.)	52 $\pm$ 3
(4) Width of Lock	2" $\pm$ 1/8"

Fabric Dimensions, Expanded

(1) Number of Cells	12 $\pm$ 0
(2) Cell Height (inches)	16 $\pm$ 1/4
(3) Cell Width, Center Cells (In.)	12 3/4 $\pm$ 1/4
(4) Cell Width, Outer Cells (In.)	15 3/4 $\pm$ 1/4
(5) Width of Tab Beyond Outer Cells (Inches, Minimum)	3
(6) Fabric Width, Not Including Tabs (Inches)	159 $\pm$ 3
(7) Fabric Length, Measured On Inside Face (Feet)	36 +2 -0

Fabric Dimensions, Inflated (Restrained)

(1) Fabric Width, Not Including Tabs (Inches)	154 $\pm$ 3
(2) Inside Radius (Ft.)	10 $\pm$ 1/2

Defects

(1) Face Fabric Openings That May Affect Coating (Slits, Tears, Holes, etc.) After Repairs Not to Exceed	0.03 sq. in.
(2) Missing Picks & Fill Yarns Shall Be Replaced	

5.1.10 Cont'd.

Defects Cont'd.

- (3) Fabric Faces & Webs Shall Not be Locked Together. Repairs Shall be Allowed.
- (4) Fabric After weaving & Repairing Shall Withstand Inflating Pressure of 2 PSI Without Evidence of Defective Webs or Failure in Faces.

Other Requirements

- (1) Fabric Weight, Based on $2.33 \pm .15$
Weight of Complete Fabric
Length (Lb /Lin. Ft.)
- (2) Inner Face Fabric to be Indexed Every Foot at One Tab End
- (3) Band of Glass Fill Yarn to be Woven in at Beginning and End of Fabric Length

6.0 PROJECTED COSTS

6.1 It is difficult to make a firm estimate of production costs because of unknown variables such as quantities and delivery rates required and probable fluctuations in material and labor costs in forward type of estimating. For example, if the quantity and scheduling would require multi-loom operation, say over 5 looms, a different arrangement for warping would be employed. Also, the operation would be somewhat less than for a single loom plant. Nevertheless, by making certain assumptions, a realistic rough order of magnitude estimate can be made.

These assumptions are as follows:

- (1) The basic fabric design of this program would be used.
- (2) One shuttleless loom would be used.
- (3) Warp beams and creels would be used.
- (4) Materials and labor rates are at present 1975 levels.

6.2 Facilities required for such an operation would include the following:

Shuttleless loom including head, installed \$35,000

6.2 Cont'd.

Modifications and Loom Accessories and Other Equipment

Needed:

Take Up & Drive	\$12,000
Cloth Winding Device	\$ 3,000
Creels for Webs (4,000 Ends)	\$ 6,000
Beam Stands and Let Off (9,000 Ends)	\$ 8,000
Drive	\$ 3,000
Harness Frames, Heddles & Reed	\$ 5,000
Warp Stop Motion	\$ 6,000
Section Warper & Creel	\$25,000
Winding Equipment	\$15,000
Inspection Equipment & Repair Tables	\$ 2,000
Engineering 1200 Hrs. @ \$13.50/Hr.	\$16,200
Plant Rearrangement & Contingencies	<u>\$13,800</u>
	\$150,000

The unit cost without amortization of facilities would be as follows:

(The following is based on a production rate of 4 1/2 lineal feet per hour and a part length of 36 feet (inner face).

<u>Labor (Including Burden & G & A)</u>	<u>\$/Length</u>
Weaving, Loom Fixing, Warping, Winding, & Creeling, Repairing, Inspecting, & Engineering Liaison	
78 Hours @ \$13.50/Hr.	\$ 1,053
<u>Material (Including G & A)</u>	
36 Ft x 2.33 Lb /Ft + Allowance for Float Yarns & Scrap = 95 Lb @ \$3.50/Lb.	<u>\$ 332.</u>
	\$ 1,385
Profit	<u>\$ 155</u>
	\$ 1,540

6.2 Cont'd.

The above single loom operation costs cover facilities that would produce 1 part per shift per day. The yearly capacity on a multi-shift operation would be about 700 to 750 parts. Space required for this type of operation would be about 15,000 to 20,000 square feet.

- 6.3 The above facility costs might be lowered about 15% if suitable used equipment is available. The unit costs might be reduced about 10% if weaving efficiency can be increased with experience and if a source of finished yarn could be developed that might reduce the yarn cost 10 to 15%. How these estimates relate to the costs of complete shelters, of course, will depend upon the analysis of coating and fabricating costs. Setting up a facility for this type of operation would have to include other considerations such as whether a standby loom should be provided and/or whether additional looms and related equipment should be available for other size shelters. In any case, it appears that this approach to making double wall inflatable shelters is economically feasible.

7 SUMMARY AND CONCLUSIONS

The objective of demonstrating the feasibility of weaving full-width double-wall inflatable fabric module sections was achieved. Considerable mechanical problems were encountered and overcome in adapting a conventional wide fly shuttle loom with Jacquard programming for this effort. The concept of using draw rolls to pull the two fabric faces at different speeds was proved to be sound, and parts were made reasonably close to target dimensions. A shuttleless loom modified to accept draw rolls, and equipped with conventional harnesses, appears to be the best candidate equipment for weaving this type of fabric in production quantities. Yarns to the loom would be supplied both

7.0 Cont'd.

from yarn creels and from beams. Fabric modules woven this way appear to offer an economical basic starting material for making inflatable shelters having a high level of reliability.

8.0 APPENDIX (Following pages)

8.1 Patent 3,538,957

8.2 Preliminary Calculations to Determine Inflated Dimensions

United States Patent

(11) 3,538,957

[72] Inventor **Walter A. Rheurne**
Los Angeles, California
 [21] Appl. No. **753,390**
 [22] Filed **Aug. 19, 1968**
 [45] Patented **Nov. 10, 1970**
 [73] Assignee **Hitco**
a corporation of California

[54] **THREE-DIMENSIONAL WOVEN FABRIC**
9 Claims, 5 Drawing Figs.

[52] U.S. Cl. **139/384,**
139/410
 [51] Int. Cl. **D03d 3/00,**
D03d 11/00
 [50] Field of Search. **139/384,**
384.1, 408-413, 20; 161/90 91. 69

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Primary Examiner—James Kee Chi
Attorney—Fraser and Bogucki

ABSTRACT: A three-dimensional fabric suitable for forming part of a hollow walled structure is woven in the form of longitudinally extending dual-layered fabric having integrally woven longitudinal ribs between the layers. The layers may have different lengths by virtue of different fiber densities in the top and bottom layers or by different total fiber counts in the two layers.

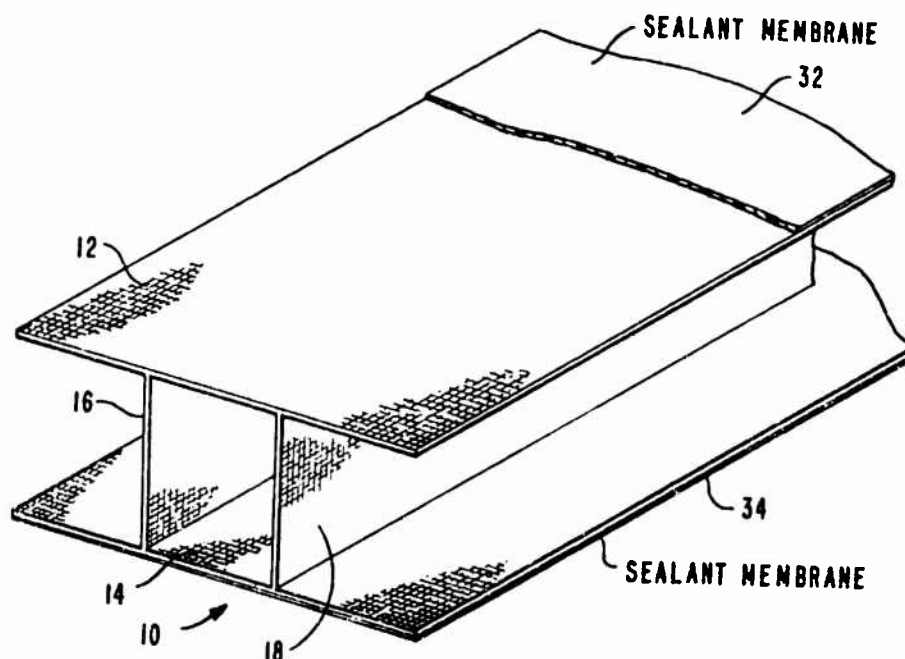


FIG. - 1

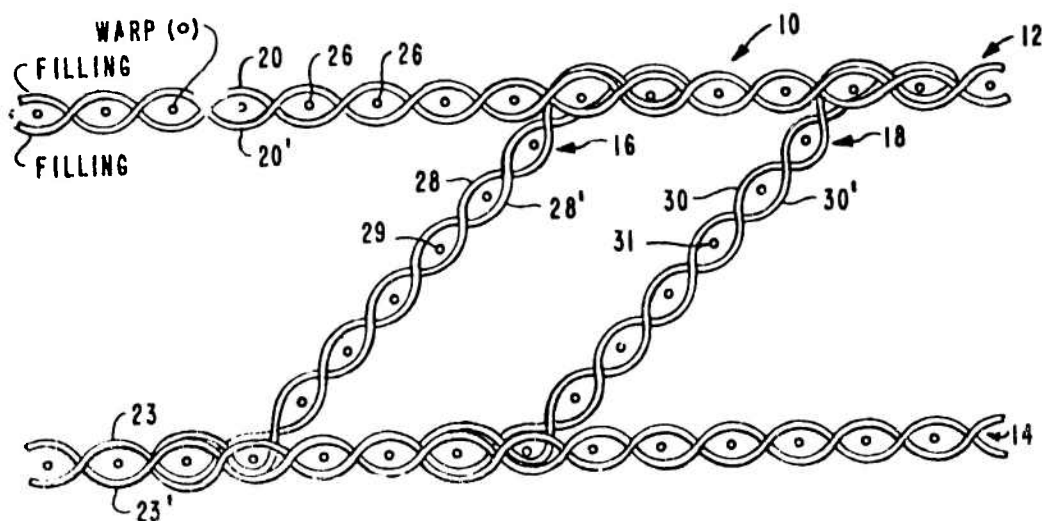
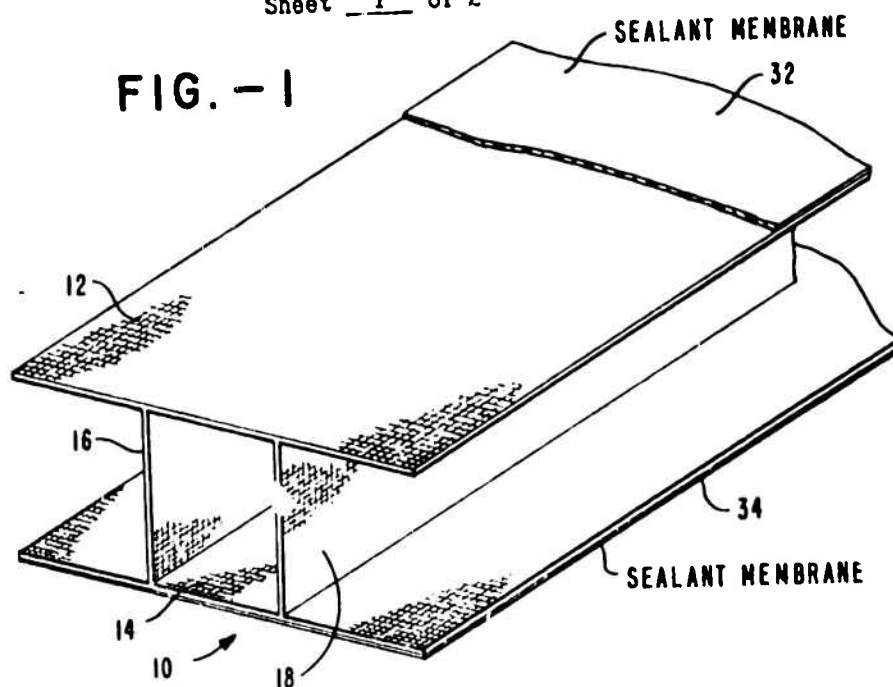


FIG. - 2

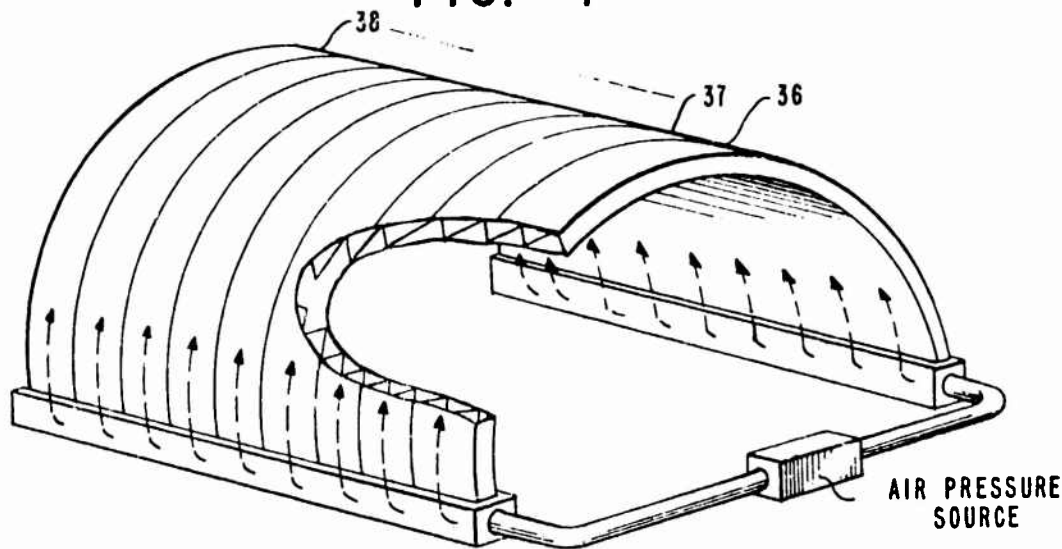
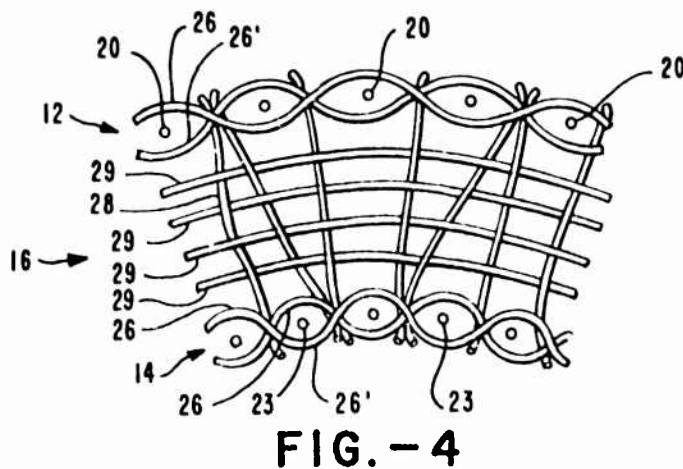
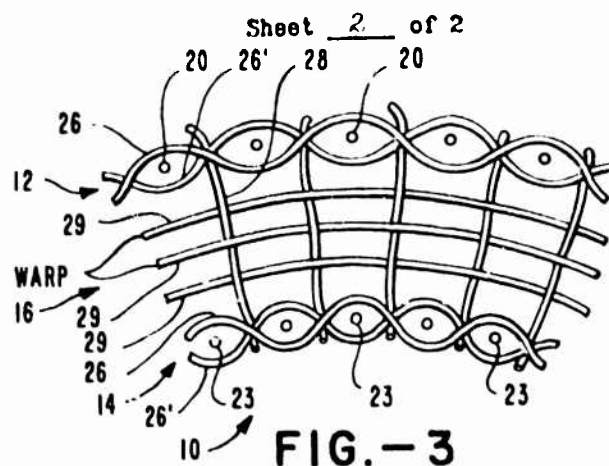


FIG. - 5

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THREE-DIMENSIONAL WOVEN FABRIC

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to fabric materials and particularly to three-dimensional fabrics useable as air supportable or expandable members.

2. Description of the Prior Art

An inflated or expanded structure employing fabric walls are being increasingly employed for both large scale structures and relatively small scale components. It is often advantageous in terms of cost and convenience to utilize an inflated construction which is air supported by suitable pressure means. If the inflated structure is formed as an arch only the longitudinal edges need be joined to a supporting structure. The material constituting the structure is formed to have internal conduits which are expanded by the air pressure to cause the assembly to rise and assume the desired shape, after which air flow is needed only to compensate for relatively minor losses. Constructions of this kind generally utilize lightweight fabrics, such as nylon, which have been treated with a sealant material such as synthetic rubber or which have been covered with a coating or adhesively attached film of a material impervious to air.

Several significant practical disadvantages arise in most conventional constructions of this type. The interior conduits are generally defined by webs or ribs that are either sewn or adhesively bonded to outer and inner exterior layers, and it is extremely difficult to obtain the desired uniformity of strength throughout the large number of bonded areas needed for a structure of typical size. Air-inflated structures of this type have been fabricated which are from 20 to 50 feet across and 50 to 100 feet long, and much larger structures are contemplated. A weak point at any of the numerous bonds within the interior structure results in a tear, which immediately induces disproportionate stresses and leads to catastrophic failure virtually immediately after full pressurization. Bonds and seals of this nature are also adversely affected by wear and aging, and the necessary inspection and repair techniques are themselves expensive and time consuming. A need therefore exists for superior three-dimensional fabric constructions having greater strength, reliability and uniformity at comparable cost.

Air-supported units are also widely used in a number of other applications, such as air mattresses, cushions and shock absorbing units. While it is preferable in many instances to have interior webs, constructions of this type are not now predominantly used because of added expense and because they are subject to the same difficulties previously discussed in conjunction with large-scale structures.

SUMMARY OF THE INVENTION

Three-dimensional fabrics in accordance with the invention have a selected transverse width and comprise top and bottom fabric layers and at least one integral intermediate fabric rib running longitudinally along the fabric and interwoven in the top and bottom layers. The warp yarns run parallel to the longitudinal axis of the fabric, and fill yarns of the interior ribs are integrally interwoven along selected distances with the top and bottom layers.

Further in accordance with the invention, different layer lengths are used to cause the fabric to have a natural arc when expanded. This is preferably provided by the use of different pick counts per inch while maintaining the same total number of picks relative to a given length along the central plane of the fabric. In another example, differential lengths are provided while using the same pick counts per inch in the two layers.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the invention may be had by reference to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a broken-away perspective view of a fragment of a three-dimensional fabric in accordance with the invention, shown in expanded form.

FIG. 2 is an idealized end sectional view of the three-dimensional fabric of FIG. 1, showing the relationship of the yarns therein;

FIG. 3 is an idealized side sectional view of a portion of the fabric of FIG. 1, showing the relationship of the yarns in a first type of fabric in accordance with the invention;

FIG. 4 is an idealized side sectional view of a portion of the fabric of FIG. 1, showing the relationship of the yarns in a second type of fabric in accordance with the invention; and

FIG. 5 is a perspective view, partially broken away, of a fragment of an air-supported structure employing fabrics in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

In FIG. 1, to which reference is now made, there is shown a three-dimensional fabric 10 lying along a longitudinal axis, but rectangularly expanded. Under normal conditions of air expansion, surfaces subject to differential pressure would of course tend to curve. The fabric 10 is preferably, for air-supported structures, woven of small-diameter fibers having suitable weather-resistant properties, either inherently or by virtue of applied coatings. Nylon and other synthetic fabrics are preferred for these reasons and because of their relatively high strength to weight ratios.

It may be seen that the length of fabric 10 in the open expanded form shown, comprises a top layer 12 or upper broad wall and a bottom layer 14 or lower broad wall, together with interior ribs or webs 16, 18. The terms "top", "bottom", "upper" and "lower" are used for ease of reference only in the specification and claims and it is to be understood that the relative attitude of the fabric is not of significance. The direction of weaving is along the length of the fabric 10, which therefore has a central longitudinal axis parallel to the selvedge. Normally the top and bottom layers 12, 14 and the ribs 16, 18 are woven in flat superimposed relation. The ribs 16, 18 are integrally woven with at least parts of the top and bottom layers 12, 14 and lie parallel to the longitudinal central axis. In contradistinction to other three-dimensional fabric constructions such as evidenced in U.S. Pat. No. 3,234,977 and 3,090,406, the woven fabric disclosed herein dispenses the warp yarns parallel to the longitudinal axis and the selvedge, instead of transverse thereto.

Details of the yarn disposition are shown in idealized form in FIG. 2, in which the top and bottom layers 12, 14 of the fabric 10 are slightly transversely displaced, with the ribs 16, 18 being angled in a position intermediate that of the unexpanded product immediately after weaving and the expanded position shown in FIG. 1. FIG. 2 illustrates a cross section transverse to the longitudinal axis, but for ease of illustration employs different and greatly enlarged scale. In actuality, for most large air-supported structures the width of the top and bottom layers 12, 14 will be substantial (e.g. 4 feet), and the interior ribs 16, 18 will also be proportionally large, (e.g. 2 feet). In a typical example there are approximately 25 ends per inch and 25 picks per inch in the fabric surfaces forming parts of the three-dimensional fabric 10. Thus it will be seen that in FIG. 2 the overall size of the three-dimensional fabric 10 has been greatly reduced and the relative number and density of the warp and fill yarns per inch greatly reduced in order to show the relationships involved. In this given cross section, the fill yarns 20, 20' in the upper layer extend transversely across the length of the layer with respect to the longitudinal axis of the fabric 10. The same is true of the fill yarns 22, 23' in the bottom layer 14. Warp yarns 26 in these layers are disposed substantially parallel to the longitudinal axis.

The ribs 16, 18 have fill yarns 28, 28' and 30, 30' respectively woven about the interspersed rib warp yarns 22, 23', the terminal portions of these fill yarns 28, 29 being woven integrally into parts of each of the top and bottom layers 12, 14.

A number of factors determine the length of this interweave, but adequate anchoring to provide an effectively integral structure typically results if there is approximately 1 inch of interwoven segment in a large-size fabric of the type previously mentioned. The length of the interweave part can be increased or reduced as desired. In the present idealized example, only two interwoven picks have been shown for simplicity.

It will also be recognized that the fill yarns 20, 20' and 23, 23' in each layer are woven to form a selvage at each longitudinal end, and do not simply terminate as shown. Further, the terminal portions of the rib fill yarns 28, 30 loop into the succeeding pick in conventional fashion.

The fabric 10 also is distinctive in that differential lengths top and bottom layer lengths are employed. In a preferred form, these differential lengths are such that the top layer 12 is longer than the bottom layer 14 by virtue of a different pick count per inch, with the two layers 12, 14 having the same total number of picks. Consequently, from the bottom layer 14 to the top layer 12, the pick density within the integrally joined ribs 16, 18 varies progressively. With respect to a central plane intersecting the expanded three-dimensional fabric 10 of FIG. 1 at the midheight point, the top layer 12 is longer and the bottom layer 14 is shorter, in this example, than the fabric length along the central plane. The ribs 16, 18 expand progressively in length from the bottom layer 14 to the top layer 12.

For a better understanding of this relationship, reference should be made to FIG. 3, in which a side section of the fabric 10 is shown in idealized form, to illustrate the yarn relationship and the natural curvature of the fabric. The fill yarns 28 of the rib 16 run longitudinally, but the warp yarns run between the top and bottom layers 12, 14, looping about the longitudinal warp yarns 26. However, the loop ends also are interwoven with a selected number of picks in each of the top and bottom layers in directions parallel to the transverse fill yarns 20, 23, which interweaving is not shown in FIG. 3. The density of the bottom layer 14, in picks/inch is greater than that of the top layer 12, while the density of the rib varies progressively between the layers. The two fabric layers do, however, have the same total number of picks.

In the alternative form of FIG. 4, the weaving schedule is arranged to introduce added picks per inch in the top layer 12, thus maintaining like densities in the two layers, while also giving a differential length relationship. When picks are differentially added in this manner, however, the weaving pattern is arranged to skip loops as the rib fill yarns 28 work between the top and bottom layers, thus also providing progressively changing rib fabric characteristics through the rib height.

The fabric 10 is rendered air impermeable by the application of sealing membranes 32, 34 on the top of the top layer 12 and on the bottom of the bottom layer, as shown generally in FIG. 1. Consequently, when pressurized air is injected into the interior conduits defined by the ribs and walls, the fabric 10 expands to lie curved about a selected radius. As shown in FIG. 5, when adjacent and adjoined fabric arches 36, 37, 38 are expanded in this manner they provide a strong shape-retaining arched structure.

As described in U.S. Pat. Nos. 3,234,972 and 3,090,406 and the patent references therein, fabrics in accordance with the invention may be provided by three-dimensional weaving utilizing standard looms controlled by predetermined patterns in fashion well understood by those skilled in the art. The basic two-rib construction shown in FIGS. 1 and 2 is preferably provided by weaving the individual layers substan-

tially flat, using one individual shuttle for each layer. Lesser or greater numbers of ribs can be provided, but in each such instance it is preferred to use a corresponding number of shuttles.

Although the invention has been described above in terms of a three-dimensional fabric having specific features, it will be appreciated that the invention is not necessarily limited thereto but embraces all forms and variations falling within the scope of the appended claims.

I claim:

1. A three-dimensional fabric having a selected transverse width, said fabric comprising top and bottom fabric layers and at least one integral intermediate fabric rib running longitudinally therealong and joining said layers, each said fabric rib being independent of the other ribs and the opposite extremities thereof terminating within said layers.

2. The invention as set forth in claim 1 above, wherein the warp yarns of said layers and said intermediate fabric rib run longitudinally and said ribs are interwoven with said layers for selected transverse distances.

3. A three-dimensional fabric suitable for expansion into a curvilinear body and having a selected transverse width, said fabric comprising upper and lower fabric layers, at least one integral intermediate rib running longitudinally therealong, the fill yarns of said at least one rib being interwoven about the warp yarns of the upper and lower layers through a selected transverse dimension and each said rib terminating within each such layer, and the warp yarns in each of the layers lying substantially parallel to the longitudinal axis.

4. A three-dimensional fabric having a selected transverse width, said fabric comprising top and bottom fabric layers each having warp yarns running substantially parallel to the longitudinal axis of the fabric, at least one integral intermediate fabric rib running substantially parallel to the longitudinal axis of the fabric, and having warp yarns running substantially parallel to said longitudinal axis and fill yarns interwoven with the yarns of the top and bottom layers through selected transverse distances along each of the top and bottom layers, said at least one rib terminating within each such layer.

5. The invention as set forth in claim 4 above, wherein the lengths of the top and bottom layers of said fabric vary differentially with respect to the fabric length along a central plane thereof.

6. The invention as set forth in claim 5 above, wherein the top and bottom layers have different pick counts per inch and substantially the same total number of picks for a given length of fabric along the central plane.

7. The invention as set forth in claim 5 above, wherein the top and bottom layers have substantially the same number of picks per inch, and the top layer has a selected greater proportion of total number of picks to the total number of picks in the bottom layer, with respect to a given length of the fabric along the central plane.

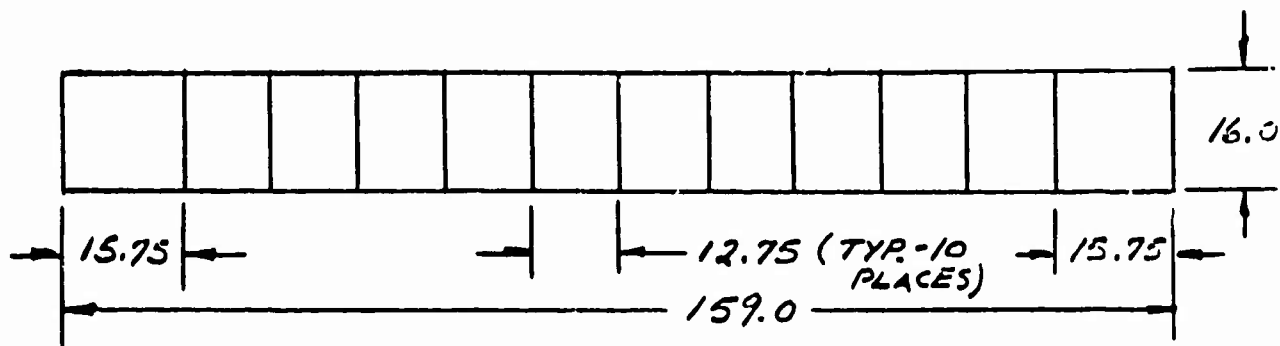
8. The invention as set forth in claim 6 above, wherein there are two fabric ribs, each lying on an opposite side of the longitudinal central axis and substantially parallel thereto, and wherein the density of the rib fabrics in picks per inch varies progressively in the direction between the top and bottom layers.

9. The invention as set forth in claim 7 above, wherein loops in the fill yarn of the rib fabrics are selectively dropped relative to the longer layer to vary the effective density of the rib fabrics in the direction between the top and bottom layers.

RFI INFLATIBLE SHELTER

UNINFLATED SIZE

(AS WOVEN)

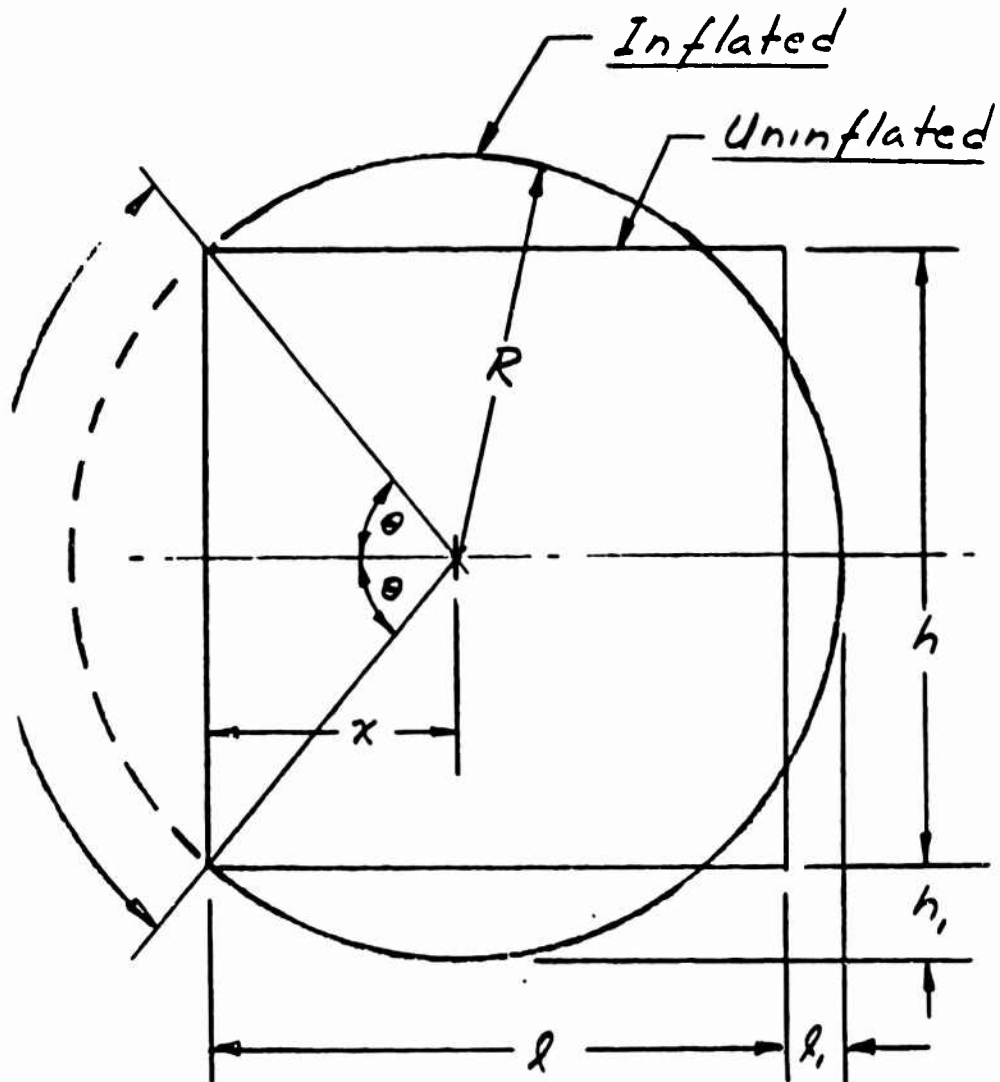


INFLATED SIZE

Inflated sizes of the end & intermediate cells are calculated by assuming:

1. The stress in the woven nylon fabric is negligible under the 2 psi inflatable pressure, hence, the strains are ignored.
2. All internal vertical webs are under tensile load and do not bow in either direction.
3. Inflated and uninflated perimeters are identical, however, inflation affects the length and height dimensions.

END CELL



Uninflated Perimeter -

$$P_u = 2l + 2h$$

Inflated Perimeter -

$$P_i = 2\pi R - s + h$$

$$s = 2R\theta$$

$$P_i = 2\pi R - 2R\theta + h$$

$$= 2R(\pi - \theta) + h$$

$$\sin \theta = \frac{h}{2R} \quad R = \frac{h}{2\sin \theta}$$

$$P_i = \frac{h}{\sin \theta} (\pi - \theta) + h$$

Equating Perimeters -

$$P_u = P_i$$

$$2l + 2h = \frac{h}{\sin \theta} (\pi - \theta) + h$$

$$2l + h - \frac{h}{\sin \theta} (\pi - \theta) = 0$$

$$l = 15.75 \text{ in.}$$

$$h = 16.0 \text{ in.}$$

$$2 \times 15.75 + 16 - \frac{16}{\sin \theta} (\pi - \theta) = 0$$

$$47.5 - \frac{16}{\sin \theta} (\pi - \theta) = 0$$

Solving for θ -

$$\theta = 49^\circ 54' = 0.8708 \text{ rad.}$$

$$\sin \theta = 0.7649$$

$$R = \frac{16}{2 \times .7649} = \underline{10.46 \text{ in.}}$$

$$x = \frac{h}{2 \tan \theta} \quad \tan \theta = 1.1875$$

$$= \frac{16}{2 \times 1.1875} = \underline{6.74 \text{ in.}}$$

$$\begin{aligned} h_1 &= \frac{2R - h}{2} = R - \frac{h}{2} \\ &= 10.46 - \frac{16}{2} = \underline{2.46 \text{ in.}} \end{aligned}$$

$$\begin{aligned} l_1 &= R + x - l \\ &= 10.46 + 6.74 - 15.75 = \underline{1.45 \text{ in}} \end{aligned}$$

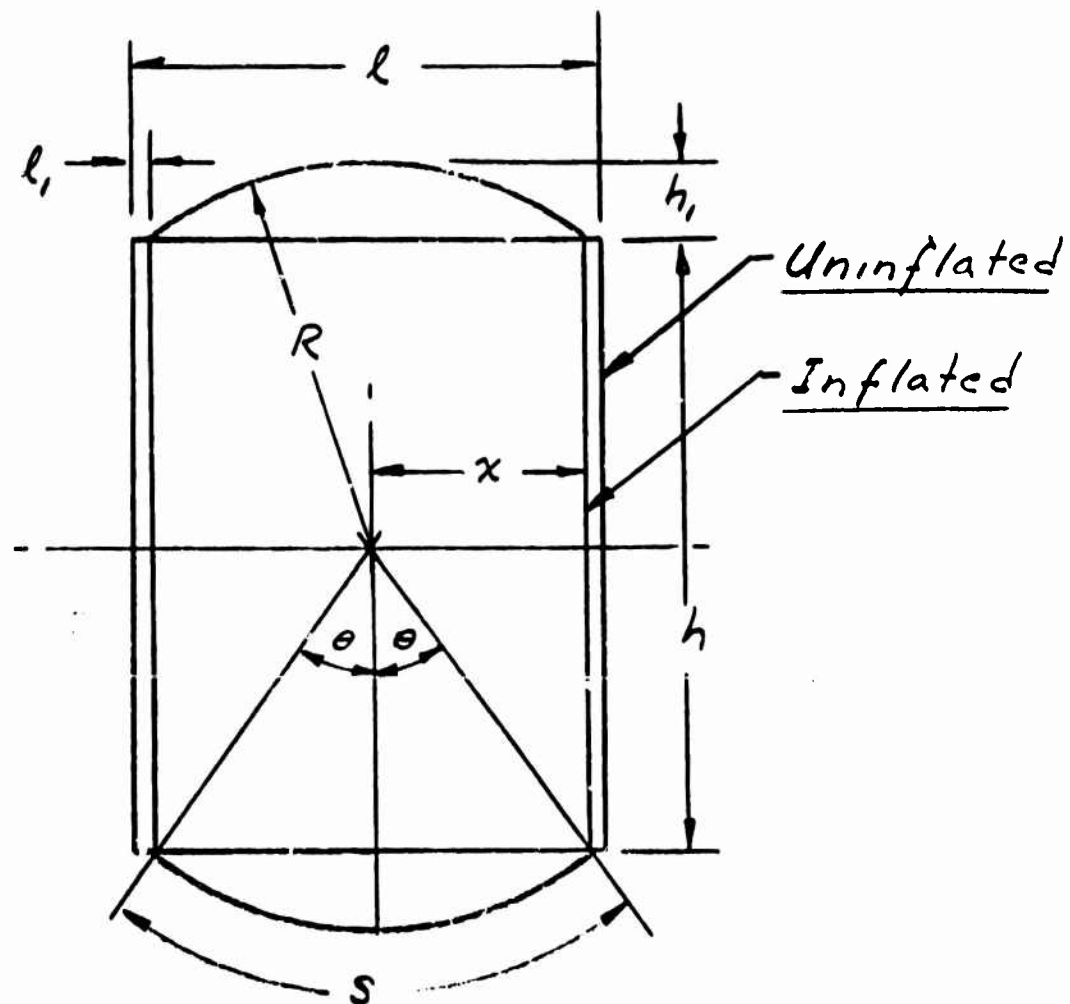
$$S = 2R\theta = 2 \times 10.46 \times .8708 = \underline{18.22 \text{ in}}$$

Check -

$$P_u = 2 \times 15.75 + 2 \times 16 = 63.50 \text{ in.}$$

$$P_i = 2\pi \times 10.46 - 18.22 + 16 = 63.50 \text{ in.}$$

INTERMEDIATE CELL



Uninflated Perimeter -

$$P_u = 2l + 2h$$

Inflated Perimeter

$$P_i = 2h + 2s$$

$$s = 2R\theta$$

$$P_i = 2h + 4R\theta$$

$$\cos \theta = \frac{h}{2R}$$

$$R = \frac{h}{2 \cos \theta}$$

$$P_i = 2h + \frac{2h}{\cos \theta} \theta$$

Equating Perimeters -

$$P_u = P_i$$

$$2l + 2h = 2h + \frac{2h\theta}{\cos \theta}$$

$$2l - \frac{2h\theta}{\cos \theta} = 0$$

$$l = 12.75 \text{ in.}$$

$$h = 16.0 \text{ in.}$$

$$2 \times 12.75 - \frac{2 \times 16 \theta}{\cos \theta} = 0$$

$$25.5 - \frac{32\theta}{\cos \theta} = 0$$

Solving for θ -

$$\theta = 36^\circ 39' = .6395 \text{ rad.}$$

$$\cos \theta = .8023$$

$$R = \frac{16}{2 \times .8023} = \underline{9.97 \text{ in.}}$$

$$x = \frac{h}{2} \tan \theta \quad \tan \theta = .744$$

$$= \frac{16 \times .744}{2} = \underline{5.95 \text{ in}}$$

$$S = 2 \times 9.97 \times .6395 = \underline{12.75 \text{ in}}$$

$$h_1 = R - \frac{h}{2} = 9.97 - \frac{16}{2} = \underline{1.97 \text{ in.}}$$

$$l_1 = \frac{l}{2} - x = \frac{12.75}{2} - 5.95 = \underline{0.425 \text{ in}}$$

Check -

$$P_u = 2 \times 12.75 + 2 \times 16 = 57.5 \text{ in.}$$

$$P_i = 2 \times 16 + 2 \times 12.75 = 57.5 \text{ in.}$$

TOTAL LENGTH CHANGE

$$L' = 159 + 2 \times 1.45 - 10 \times 2 \times 0.425$$

$$= 159 + 2.90 - 8.50 = 153.4 \text{ in.}$$

$$\Delta L = 159 - 153.4 = \underline{5.6 \text{ in.}}$$