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RESEARCH AND EXPERIMENTATION ON UNIQUE EXPANDABLE SHELTER CONCEPTS FOR LIMITED WAR APPLICATIONS

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UNIVERSITY OF CINCINNATI

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FOREWORD

This is the final report on Air Force Contract AF 33(615)1285 "Research and Experimentation on Unique Expandable Shelter Concepts for Limited War Applications" and includes work performed under Modification #1(65-636)-30 October, 1964. A supplementary final report will be submitted covering work performed under Modification #SA 4(65-3603) - 30 June, 1965 at the completion of the work.

This report was prepared by James M. Alexander of the Department of Industrial Design, and Karl H. Merkel of the Department of Architecture, College of Design, Architecture, and Art, University of Cincinnati, Cincinnati, Ohio.

This work performed under the Contract was administered under the direction of the Air Force Aero Propulsion Laboratory, APFT, Research and Technology Division, Wright-Patterson Air Force Base, Ohio, Mr. Fred W. Forbes, APFT, Project Engineer.

Work conducted between 23 December, 1963 and 4 September, 1965 is covered by this report.

In addition to the authors of this report the following faculty members participated in the research and experimentation work performed under the Contract: Joseph M. Ballay, Bruce E. Goetzman, and Richard H. Stevens. Laurence Fabbro, research assistant, and several upperclass co-op students of the college also made important contributions.

The authors wish to thank the Project monitors, Mr. Fred W. Forbes and 1/Lt. Anthony Zapparti, for their assistance in scheduling Air Force facilities for testing, for providing necessary supporting equipment, and lending their knowledge to the study.

This report was submitted by the authors 15 September 1965.

This technical report has been reviewed and is approved.

Robert D. Sherrill
Chief, Ground Support Branch
Support Technology Division

ABSTRACT

Lightweight expandable shelters for limited war applications are described.

Concepts for both small (16 ft wide) and large (50 ft wide) shelters are presented.

Included in the small shelter section is the development of several different geometric configurations and methods of assembly. The construction, testing, and erection of prototype shelters based on two of the concepts are covered. Both shelters described utilize plastic foamboard as the basic construction material. Data on static load tests, erection time, package cubage, and package weight are included.

Several structural concepts for the large shelter are presented. This structure, designed to serve as a hangar for a fighter aircraft, is carried through the concept stage only. The various concepts are described and sketches illustrating their key features are presented.

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I. INTRODUCTION

The period of the "cold war," characterized as it has been by limited warfare situations and counter-insurgency actions, has given rise to new thinking on the part of the armed services in the area of supporting actions in hot spots of activity by means of utilizing unconventional warfare tactics.

New and radical techniques and methods of supporting limited war are needed. This is especially true as this activity frequently occurs in remote areas of the earth that are usually inaccessible by normal transportation methods. Climatic situations encountered may vary from desert conditions to those found in tropical jungle or wet delta.

The supporting of troop operations in these extremes of climate becomes a very important consideration. The problems of support are in the areas of functional support shelters, resupply techniques, and overall logistics.

In recognition of this need for unique design concepts for small support shelters, a contract was awarded to the University of Cincinnati to develop such concepts. As the emphasis was on creative and new approaches to the problem, as opposed to refinement and detailed engineering of existing concepts; it is significant that the contract was awarded to the Departments of Architecture and Industrial Design with the participants drawn from faculty member/designers in those departments.

Following the development of several concepts, this contractor was directed (under an amendment to the contract) to build for field testing two full-size prototypes of the small general purpose shelter.

This report will cover the work performed under both the basic contract (development of concepts) and the amendment (construction and field testing of full-size prototypes).

Although the initial work in developing concepts involved concurrent studies of (1) small (personnel and general purpose) and (2) large (aircraft maintenance hangar) shelters, for clarity and continuity. The body of this report has been divided into two major sections: SMALL SHELTER CONCEPTS and LARGE SHELTER CONCEPTS. This format for the report has been further prompted by the chronology of events which, in terms of major effort, followed the sequence (1) development of concepts of both small and large shelters, (2) construction and testing of two full-size prototypes of small shelters, and (3) return to further concept-development of large shelters.

Though not covered by this report, two follow-on developments should be noted:

(1) Under a second amendment to the basic contract, this contractor is serving as prime contractor for the construction of ten small (16' x 32') shelters of a type constructed and field-tested under the first amendment to the basic contract.

(2) This contractor has been awarded a second contract to further refine previously developed concepts of the large (aircraft maintenance hangar) shelters and to produce for field-testing one full-size prototype large shelter.

II. OBJECTIVES AND DEFINITION OF THE PROBLEM

A. OBJECTIVES

The objectives of this effort were to establish unique design concepts for small support shelters usable for limited war or counter-insurgency operations, and to provide technical services, fabrication services, and any experimental apparatus for in-house experiments and analytical investigations of problems associated with the development of limited war support structures.

An expandable shelter was defined as a shelter system that has a much greater final erected internal usable volume, compared to its packaged unerected volume. Folding and modular type configurations are included in this definition.

Aspects to be considered in formulation of design concepts included

(1) The use and erection of the shelters in field conditions, sometimes under adverse weather.

(2) Ease of packaging and maintaining as favorable package size to erected volume ratio.

(3) Capability of being dismantled, repackaged, and re-erected five times.

(4) Capability of being transported in C-47 type aircraft or jeep-type vehicles.

(5) Wind loads to 50 knots and live loads of 5 to 8 psf.

Initial recommendations of sizes to be investigated included

(1) A small forward area support shelter system (175 sq ft floor area).

(2) An equipment maintenance shelter system (approximately 300 sq ft floor area).

(3) A shelter to allow an L-28 (Cessna type) aircraft to be towed or pushed into the building for maintenance.

(4) Methods of combining or expanding shelter systems for larger shelter volumes.

Specific requirements called for investigating new and creative approaches to lightweight shelters; establishing design feasibility of concepts; and preparing experimental models, test items, and consultation as authorized by the project engineer.

B. DEFINITION OF THE PROBLEM

To further determine the detailed needs of the Air Force, trips were made to two Air Force Bases. As the command most likely to eventually utilize structures based on concepts developed under the contract is the Tactical Air Command, three TAC bases were visited and appropriate personnel at each were interviewed.

(1) On 2 and 3 January, 1964 a visit was made to Eglin and Hurlburt AF Bases, Florida. Discussions were held with staff officers of Special Air Warfare Center (SAWC), 1st Combat Applications Group, and 1st Air Commando Wing. The distinction between limited warfare (conventional as opposed to atomic) and special warfare (counter-insurgency actions) was made. Prime interest of many of the officers contacted was in the latter (special warfare) category, and many of their comments and recommendations dealt primarily with shelters for this activity.

In the personnel shelter area, interest was expressed in small, lightweight, inexpensive shelters that would be capable of being turned over to indigenous forces, would be air-droppable, and would most likely be disposable.

In the area of operations and communications shelters, existing equipment was reviewed (especially the B-2A DM 1948 shelter - 16' x 16' and expandable in length in increments of 4 ft) and interest in a structure of similar capabilities but lighter weight was expressed.

Also reviewed were air drop and extraction techniques, package size limitations for these techniques, interior volumes and door opening sizes of C-46 and C-47 type transport aircraft, and governing dimensions for serving a U-10 (L-28) type aircraft.

(2) On 10 February, 1964 a trip was made to Headquarters, TAC, Langley Air Force Base, Virginia. Under the auspices of the Deputy of Engineering a conference was held with some ten staff officers from Hq. TAC, two representatives of the University of Cincinnati, and a representative of the Aero-Propulsion Laboratory, WPAFB in attendance.

At this conference a detailed presentation of the Air Force Bare Base program utilizing the "Grey Eagle" package was made.

This conference and follow-on discussions with members of the Civil Engineering group resulted in the following general recommendations:

(a) Personnel and general purpose shelters should be 16 ft wide and expandable in length.

(b) Thirty-day usage should be considered minimum but, with maintenance, a usable life of two years should be possible.

(c) Extraction on pallets from C-130 type transport aircraft was favored over air-droppable capabilities.

(d) Primary objective should be reduction of weight and bulk.

(e) The aircraft maintenance dock should be sized to accommodate the F4C type fighter aircraft rather than the U-10 (L-28) type observation aircraft.

(f) Lightweight panelized structures were favored over tent-type structures because (1) it was hoped shelter concepts developed would fill an existing gap between existing tentage and heavier conventional panel-type structures or permanent buildings, and (2) it was felt that concentration on tent-type shelters would duplicate well-developed programs in the Army and Marine Corps as well as commercial development programs in this area.

The recommendations from Headquarters TAC, placed emphasis on air-transportable reusable lightweight expandable structures for limited warfare situations as opposed to disposable air-droppable structures for special warfare situations as emphasized at Eglin.

It was felt by Hq. TAC that types built along lines of their recommendations might well find application in both limited and special warfare situations.

These recommendations from Headquarters TAC were followed and, under directions from the project engineer, concept study was started on the assumption that two basic size types would be investigated:

(a) a 16' wide general purpose shelter expandable in length

(b) a 50' x 80' x 25' high aircraft maintenance shelter.

In the following sections of the report the 16' wide shelters will be designated "small shelters" and the 50' x 80' shelters will be designated "large shelters."

III. SMALL SHELTER CONCEPTS

A. INITIAL CONCEPTS

Based on the Statement of Work in the RFP, this contractor in his original proposal had suggested several principals and approaches. These included:

(1) Rigidized or air-inflated framework with attached skin.

(2) Hinged framework with attached skin.

(3) Folded plate structures.

These three approaches were studied more extensively and potential advantages and disadvantages were considered.

1.) Rigidized or air-inflated framework with attached skin.

Further study of the state of the art of encapsulated self-foaming and rigidizing plastics revealed that basing a concept on this principle was not realistic at this time. While other contracts were developing techniques that might prove useful in the future, it was apparent that the current state of development was not such as to provide an immediately usable technique. On instructions from the project engineer no further study was made along these lines.

Examination of work being performed by the other services revealed fairly advanced work in air-inflated structures had been performed and was continuing at Army Natick and other agencies. In order to avoid duplication of effort with the other services, this approach was not pursued further.

2.) Hinged framework with attached skin.

One approach investigated employed plastic-coated steel wire frames of a size convenient for handling and provided with male and female interlock attachments so they could be assembled in groups to form a large structure. The interlock devices would be designed to collapse in one direction and become rigid in the other direction of movement of the joint. Series of such modules, slightly curved, could become an arched form of any desired radius. Tension lines at floor level could rigidize the arches, and additional arches attached laterally could result in a structure of any desired length of a quonset-type configuration.

A continuous skin material was suggested for the protective covering.

With more promising results forseeable in the folded plate approach, the hinged framework approach was set aside.

3.) Folded plate structures.

Further studies of materials (strength, weight, durability, weather-resistance, insulating quality, portability, shelf life, color, cost, availability, etc.) led to the decision to explore folded fiberboard or combination plastic and fiberboard systems. Rectangular systems were first considered. These could be produced and shipped with little difficulty. They could be arranged easily in functional, though conventional configurations and incorporating such features as complete floor areas, vertical walls with headroom as necessary, water shedding from pitched roof panels, provisions for vents and doors.

Several distinct problems quickly became apparent such as: poor rigidity and continuity of structure, assembly of certain members above-head height, and the number of different shaped and special use pieces which might cause confusion during erection. It was decided that less conventional configurations should be explored.

Folded fiberboard geodesic dome structures and variations of these were considered. Obvious disadvantages of this concept led to its early dismissal. These included: poor headroom, limited shape and size, no easy or logical means of expansion, poor access to the interior, complex field assembly of almost-but-not-quite identical parts, and complex arrangements of terminating the structure at the ground line.

The more intriguing concepts of developments of folded fiberboard (corrugated or other) structures then began with explorations of positive and negative folded panels. These panels had inherent structural characteristics and, when combined with other similar panels, resulted in configurations very adaptable to the functional requirements of the project.

B. "BOW-TIE" MODULAR CONCEPT

Preliminary studies of various geometric configurations led to a "bow-tie" shaped module which could be folded from a 4' x 10' sheet of fiberboard.

Figure 1 shows the evolution of the folded "bow-tie" module. The variation shown(1g) used about 10% less material and would result in fewer modules per shelter but gave less rigidity because of lack of continuity of the diagonal ribs.

Figure 2 shows small scale models of vault sections formed of the basic bow-tie and the variation.

The ratio of the length and width of the panel determines the angles of the three dimensional form of folded shapes. These proportions and angles can be so controlled as to develop the configurations most suited to the problem requirements.

The "bow-tie" concept offered many advantages:

(1) Only two basic modules are necessary, full panels and half-panels (exclusive of treatment of ends of shelter).

(2) Triangulated structure of the panels and continuity of the arched structure stress lines of the combined panels both indicated adequate rigidity in small scale model studies.

(3) Assembly can be made from the ground and from inside the structure.

(4) Ribs are formed by turning panel edges inward thus protecting edges of material from exposure to weather.

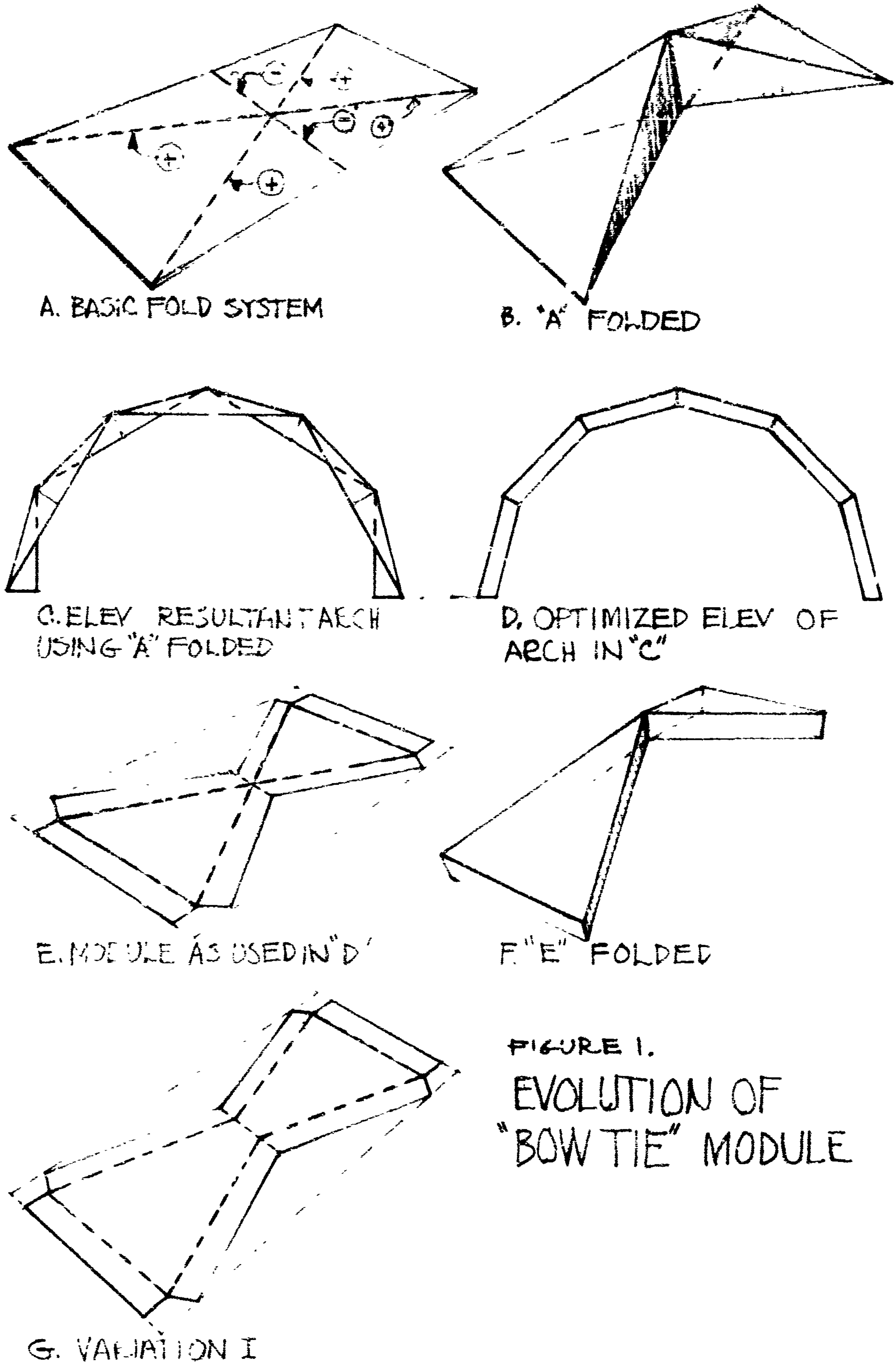


FIGURE 1.

EVOLUTION OF "BOW TIE" MODULE

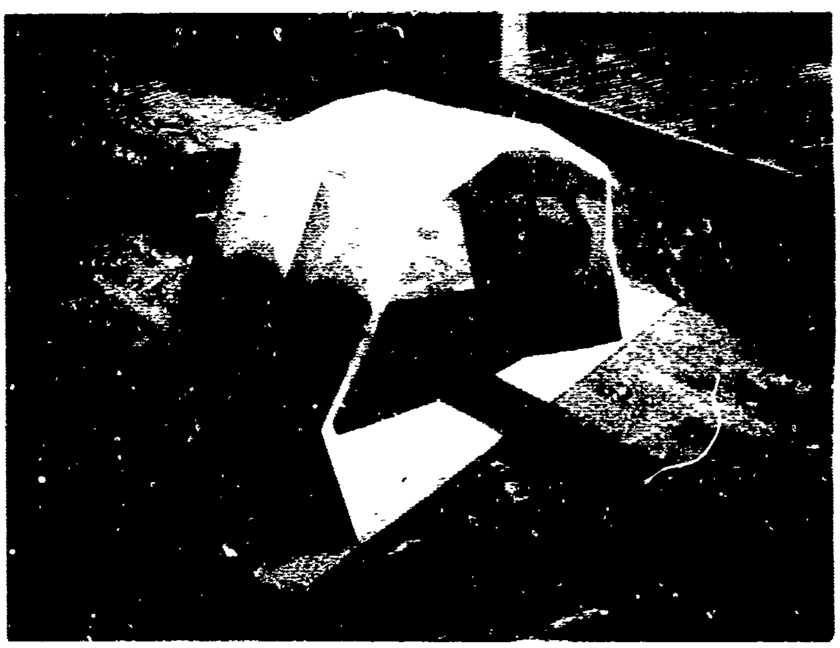


FIGURE 2 - SCALE MODELS OF SHELTER VAULT USING "BOW-TIE" MODULE (ABOVE) AND A VARIATION ON THE "BOW-TIE" (BELOW)

(5) Ribs on the interior provide opportunities for attachment of equipment, utilities, furniture, interior partitions, etc.

(6) Unlimited linear expansion.

(7) The triangulated system permits limited openings to be developed in the side walls for ventilation, windows, doors, etc. Removal of several modules and half-modules could make possible attachment of passageways to adjacent shelters.

(8) The units could be easily disassembled and repackaged flat for each reshipment.

1.) Test arch using cherry rivet connectors

The "bow-tie" approach offered prospect of success sufficient to warrant construction of one or more full-size arches. The first one constructed had an inside width of 16', an inside height of 8', and was 2 modules "long" (4' at base). The material used was Container Corporation of America W5C (B flute) corrugated fiberboard. Though not seriously considered for eventual adoption, cherry rivets with washers were used to secure adjacent modules to each other as shown in Figure 3a.

While the constructed arch sustained its own weight, serious deficiencies were noted: (1) Progressive tension failure at the "waist" of the "bow-tie" (parallel to the corrugations of the fiberboard), (2) slight compression bowing of folded ribs near base of arch, (3) considerable side sway and opening up of six-way intersections.

The low cost of the material used suggested the possibility of throw-away structures permanently joined with adhesive. As this was not within the scope of our problem, no further study in this direction was made.

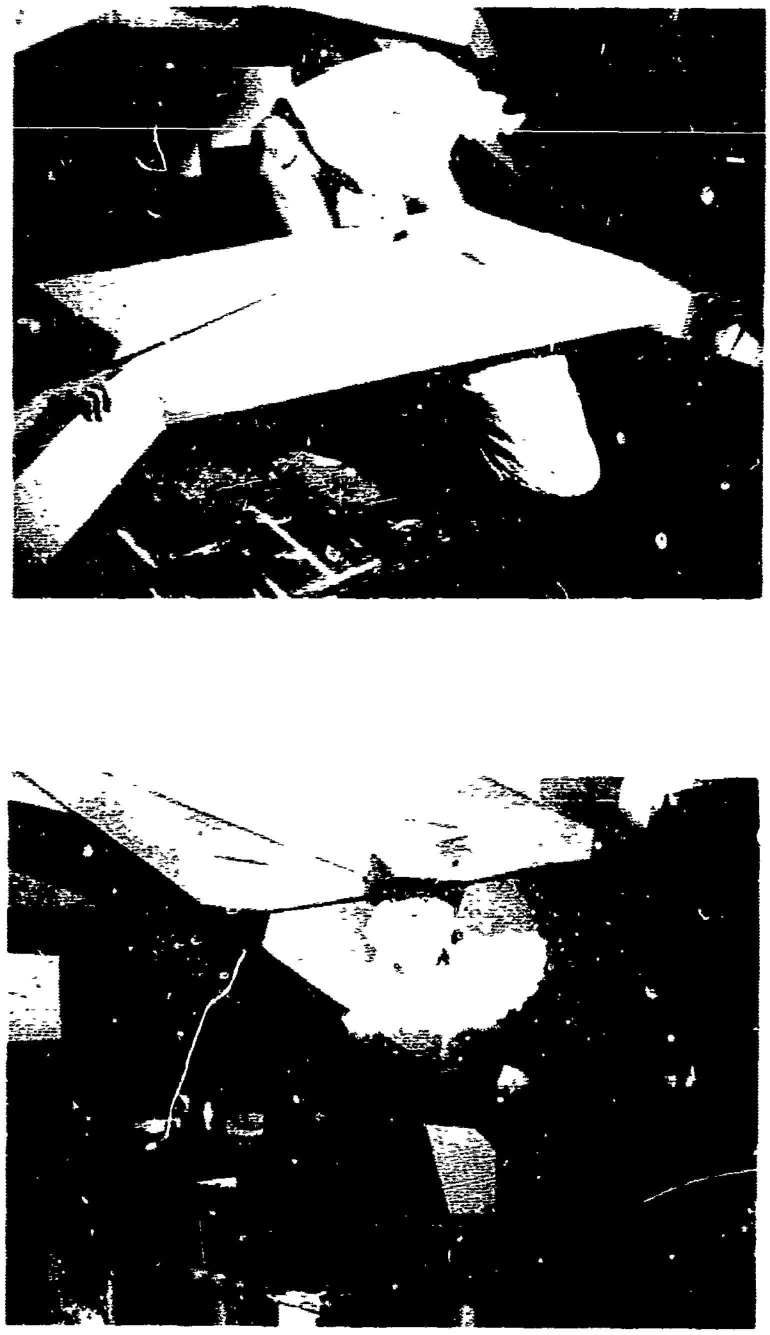


FIGURE 3. PROTOTYPE ARCHES USING CORRUGATED FIBERBOARD WITH CHERRY RIVET CONNECTORS (ABOVE) AND WITH SHEET-METAL ASTERISKS (BELOW)

It was recognized that use of other materials that did not have the directional qualities of corrugated board should overcome some of the difficulties. Tape reinforcement was experimented with as tensile reinforcement at critical points of stress. Fiberglass reinforced and 3M Filament tape were used.

The construction of the first series of arches was undertaken basically to determine the structural feasibility of the concept, the geometric configuration of the components, and possible methods of attachment. The necessary research in the areas of weather-resistant surface treatment and the weather-peeling of joints was deferred until this structural feasibility was established.

2.) Test arch using sheetmetal "asterisks"

In order to further rigidize the structure a star-shaped slip-on fastener was designed and several of these "asterisks" were fabricated for testing. The "asterisk" did succeed in rigidizing the intersections by eliminating the opening-up noted on the first arch and by taking much of the tensile stress off the waistline folds of the bow-tie modules. These connectors featured metal plates that fitted snugly over the flanges at the vertexes of the triangular panels, holding the flanges together and being locked to the flanges with bolts. This test arch is shown in Figure 3b.

Counteracting the advantage of achieving greater rigidity were several apparent shortcomings: (1) The connectors were complicated, heavy, and bulky for storage and (2) they were much stronger than the sheet material being used. Also, the weight of these connectors increased the tendency of the folded ribs of the panels to buckle in compression at the base of the test arch.

3.) Test arch using sheetmetal rib reinforcement

The next experimental arch differed from the previous ones in that a different sheet material was used: Union Carbide Techni-Foam. This material is a sandwich material consisting of two layers of 69# Kraft paper and a filler material of urethane foam. Board thicknesses obtained were 1/4 inch and 3/8 inch.

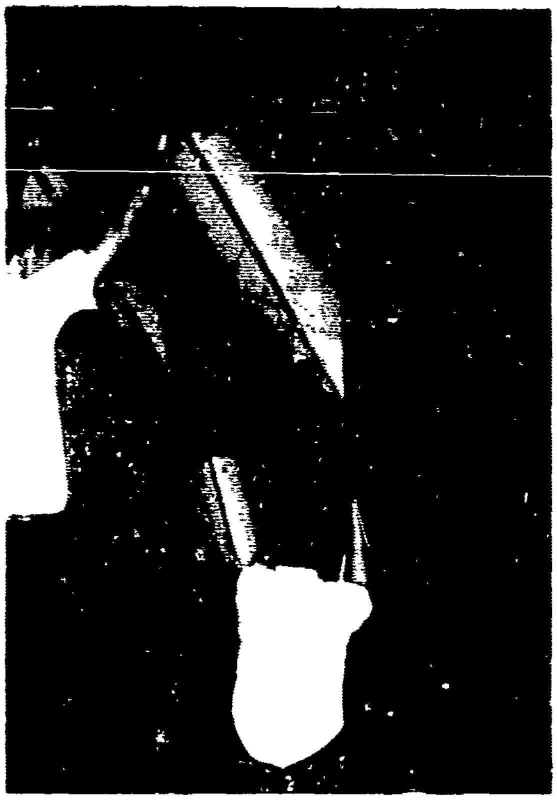
For this arch 3/8-inch thick Techni-Foam was used. The folded ribs of the "bow-tie" modules were reinforced with 28 gauge galvanized iron strips having a "J" section (2" x 3/8" x 5 1/2"). The connectors used were Simmons spring-loaded type #W7. The assembled test arch is shown in Figure 4a and c and the Simmons connector is shown in Figure 4b.

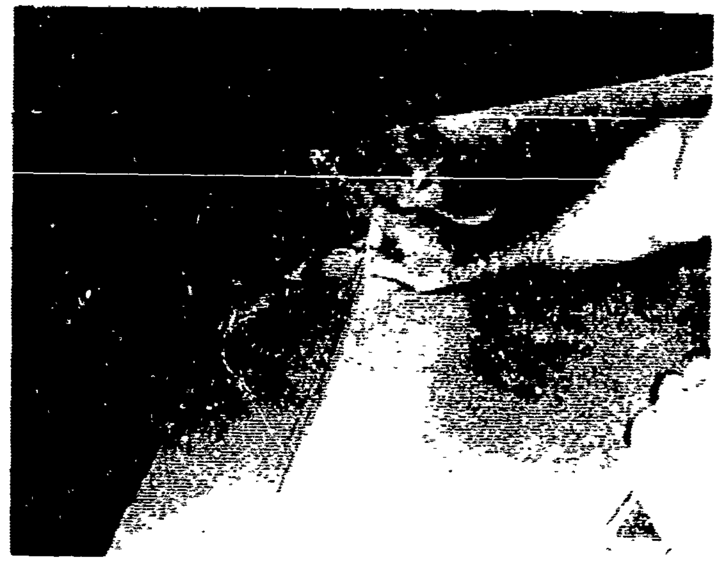
The waists of the "bow-tie" panels had a tendency to spread under tensile loading of the arch, indicating a need for a connector to hold the waist together in the finished structure and also to make the panel easier to handle during the folding up of the box prior to erection. A "hair-pin" type device was designed and used for this purpose.

Though the Simmons connectors proved a quick means of connecting if alignment was perfect, hand methods of fabrication made it impossible to achieve this degree of perfection in all cases. The structure provided fair resistance to lateral sway and good resistance to longitudinal movement.

It was decided that the design was too conservative in the amount and weight of metal added. The metal in effect took over the structural function of the folded ribs and added weight to the structure. The weight of this metal was approximately twice the weight of the Techni-Foam board required. The need for the 3/8-inch thick board was also questioned.

A further complication arising from the use of the Simmons connector, with the female half of each connector fabricated in place, was the complicated numbering of modules for erection in proper sequence.





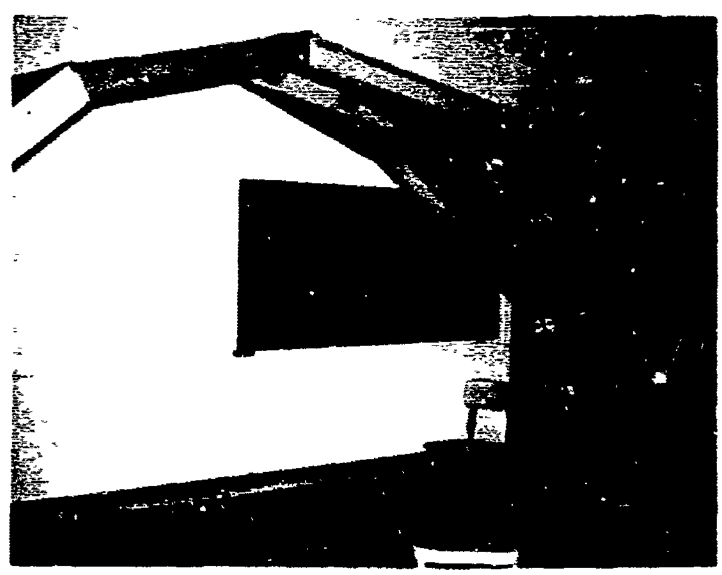


FIGURE 4. TECHNI-FOAM TEST ARCHES

a. Erection of test arch using Techni-Foam, 'J" section sheet metal reinforcement and Simmons connectors

b. Detail of Simmons connector

c. Completed arch as erected in "a" above

d. Completed Techni-Foam arch using 1" x 1/4" x 1" channel reinforcement and thumbscrew/ wingnut connectors

4.) Final "bow-tie" concept test arches

In line with the conclusions reached on the previous test arch, the following modifications were made on the next arch: (1) 1/4-inch thick Techni-Foam was substituted for the 3/8-inch material, (2) a simple thumbscrew/wingnut connector was substituted for the Simmons connector, (3) metal reinforcement was changed from galvanized steel to .020 inch aluminum and consisted of a 1" x 1/4" x 1" channel edge strip, a chevron-shaped gusset plate on each flange at the waist of the "bow-tie", and 3" square load-spreading washers at the thumbscrew locations, and (4) a 1/8" x 1" steel strap stirrup with washers and thumbscrew was designed to secure the waist of the module in its folded position. (See Figure 4d) These refinements were evolved in a series of test modules and arches, the details of the refinements being worked out in conjunction with a series of static load tests.

While this work was in progress, it was learned that Techni-Foam was being withdrawn from the market and another material had to be substituted. The material chosen was FOME-COR, a kraft paper and styrene foam sandwich board. This material was available in 1/4-inch thickness with a 42 lb liner (as compared with the 69 lb liner on the Techni-Foam). A comparison of the two materials is shown in Table I on the next page.

TABLE I

COMPARISON OF 1/4" TECHNI-FOAM AND 1/4" FOME-COR

("BOW-TIE" CONCEPT)

		1/4" Techni-Foam	1/4" Fome-Cor 420-A
1.	Weight per square ft	.202 lb	.129 lb
2.	Adhesion liner to foam	---	Superior
3.	Surface smoothness	---	Superior
4.	Resistance to chemical action	Superior	*
5.	Resistance to intense heat	Superior**	***
6.	Resistance to indenting	Superior	---
7.	Flexural strength @ elastic limit:		
	load/lbs	NA	4.80
	deflection/inches	NA	0.30
	stiffness factor EI	NA	577
8.	Moisture Absorption-% by volume	NA	4.1
9.	C Factor @ 50% R.H. BTU/Hr/Sq ft/^{o}F	NA	1.00
10.	Weight of Kraft Line lbs/MSF	69	42

*When unprotected edges exposed to certain coatings (i.e. expoxies) styrene foam melted to maximum depth of 1/4 inch.

**Urethane foam hardened and became more brittle. Paper liner curled away from foam and delaminated.

***Styrene foam melted at 180^{o} causing inward collapse of paper liner.

NA = data not available

To secure comparative structural data, identical "bow-tie" modules and test arches were constructed and subjected to static load tests. Test arches are shown in Figure 5a and test modules in Figure 5b, c, and d.

Static load tests of test arches and individual modules are shown in Tables II through VII.

5.) <u>Concurrent Investigations</u>

Concurrent with the construction, testing, and modification of test modules and arches described above, other studies were being conducted and are summarized here:

a.) Other folded plate configurations:

A bellows-type foldable configuration was investigated and full size mock-up of connecting parts were constructed. Its basic cross section was rectangular with structural load-carrying capabilities largely dependent on the transverse gable configuration of the individual module arches. It involved rather complicated folding, was self-flashing through overlapping modules but left considerable exposure of panel edges, and would have entailed a zig-zag grade beam to anchor the vertical side walls to the ground. At the 16' span size required, erection might have been awkward and structural capability was doubtful and would have to be tested full-size. The concept was deemed more appropriate for 8' or 10' span sections. It is shown in Figure 6.

b.) Other panel materials:

(1) Rigid solid fiberboard ("chestnut board" beer carton material as manufactured by Container Corporation, "Form-L" as manufactured by Mead Corporation). If budget had allowed certain special coatings and/or

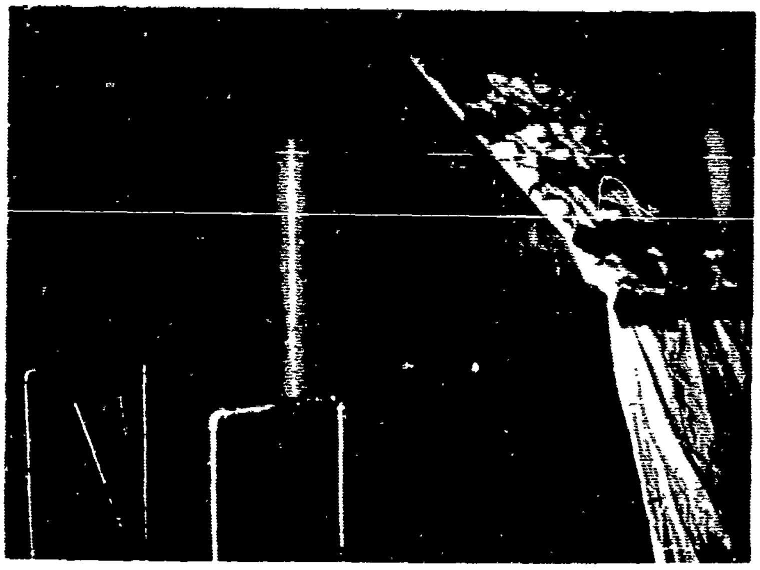
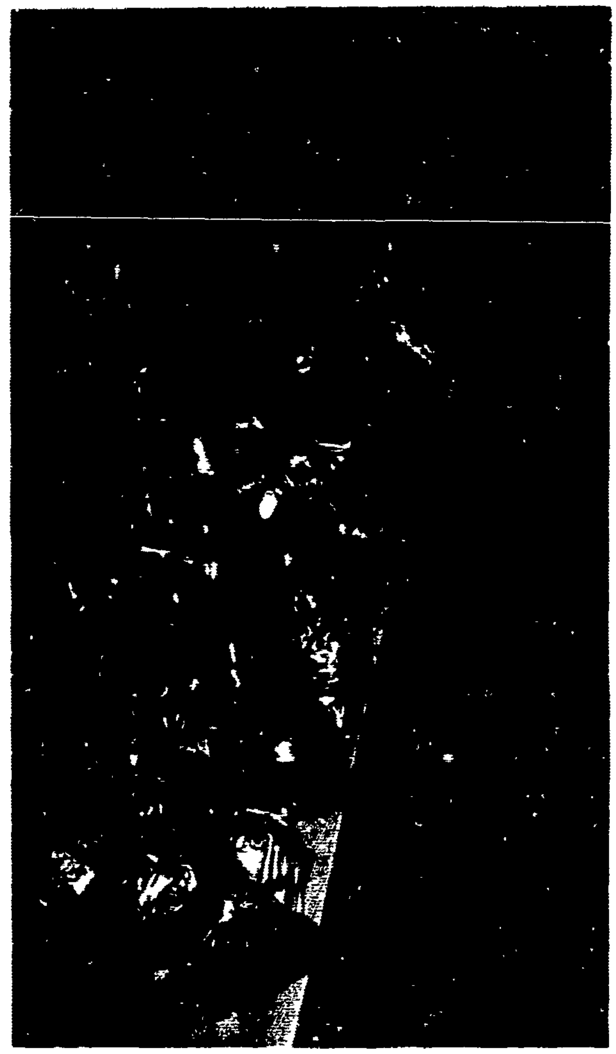



FIGURE 5. ARCH AND MODULE STATIC LOAD TESTING ("BOW-TIE" CONCEPT)

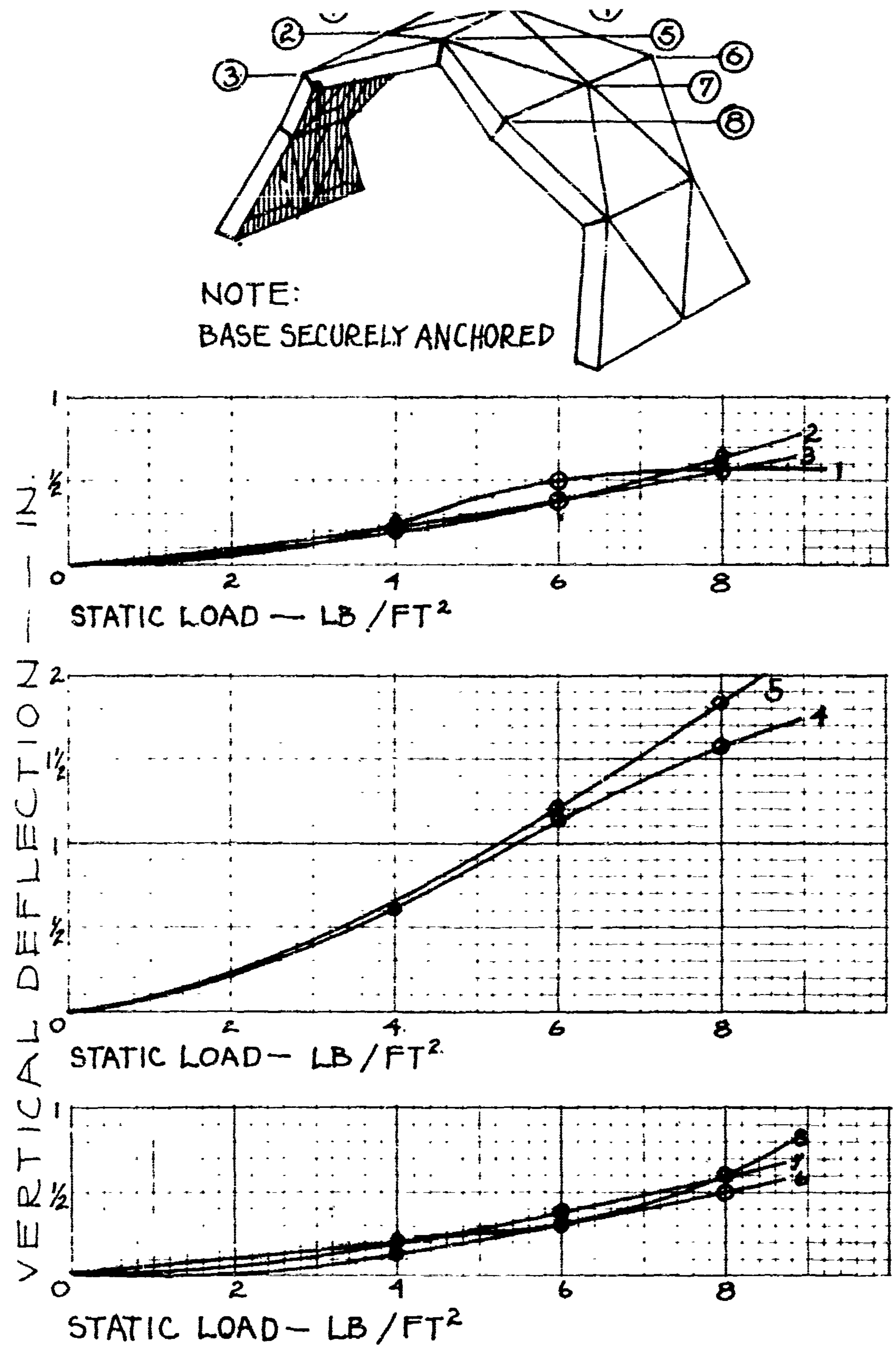
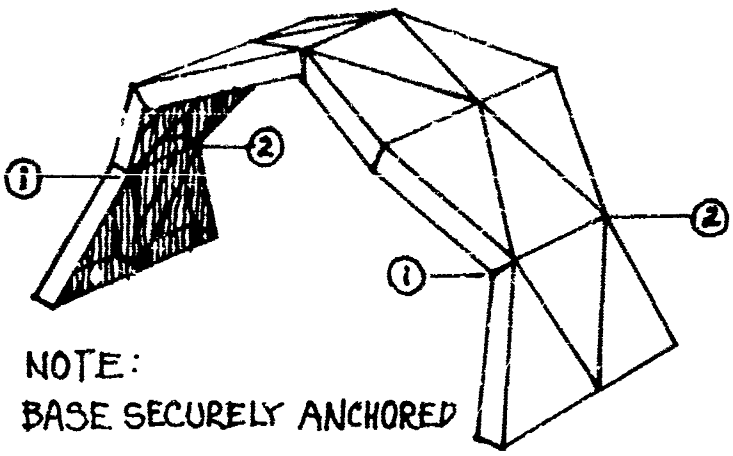


TABLE II - VERTICAL DEFLECTION TEST - TECHNI-FOAM TEST ARCH ("BOW-TIE" CONCEPT)



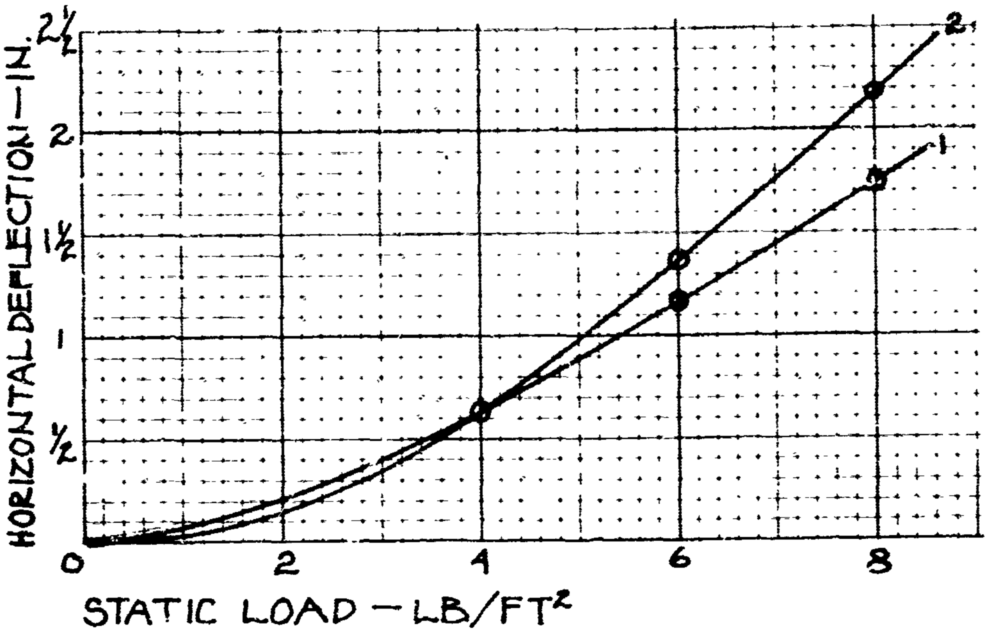


TABLE III - HORIZONTAL DEFLECTION TEST - TECHNI-FOAM TEST ARCH ("BOW-TIE" CONCEPT)

TEST DESCRIPTION (TABLES II & III)

One complete modular arch (see sketch) constructed from 1/4" Techni-Foam and reinforced with one inch galvanized steel edge channels and Kraft paper-nylon mesh tape at the central fold of the bow tie was tested by the application of a gradually increasing uniformly distributed load. As the loading approached 10#/ft^2 the center joint failed in tension tearing the reinforcing tape; the structure collapsed quite suddenly. The vertical and horizontal deflections were excessive due to a separation failure of one of the stabilizing clips at the center joint. It would appear that testing just one arch rather than a completed structure is really an unfair test; one would expect a completed structure to be capable of carrying a much larger load.

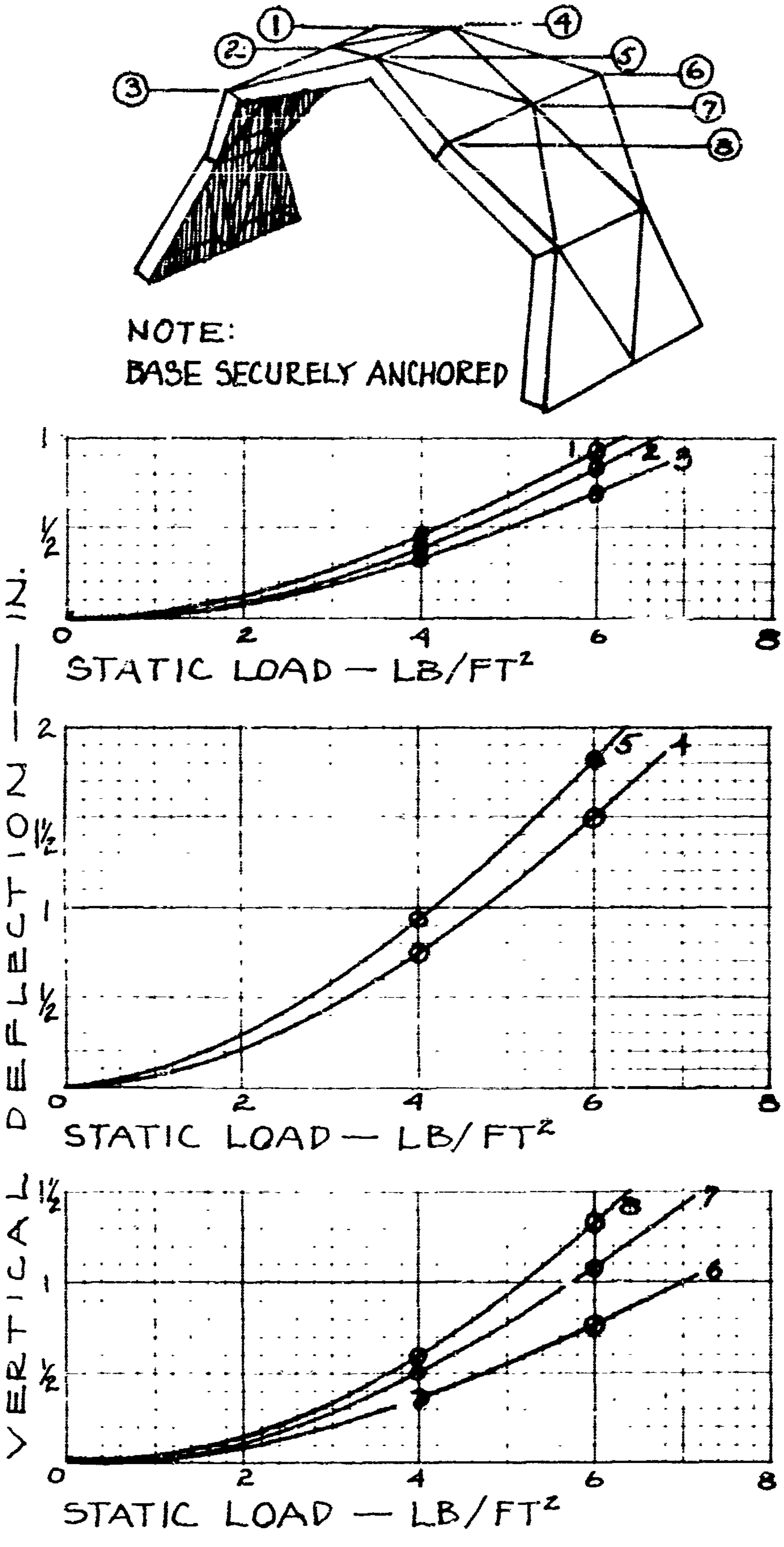
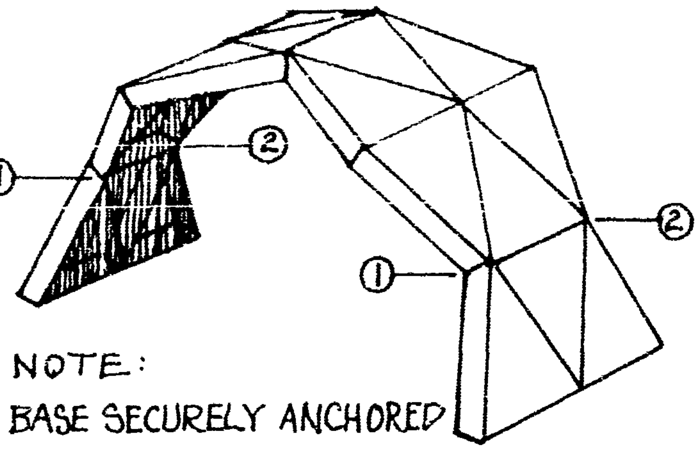


TABLE IV - DEFLECTION TEST - FOME-COR TEST ARCH ("BOW-TIE" CONCEPT)



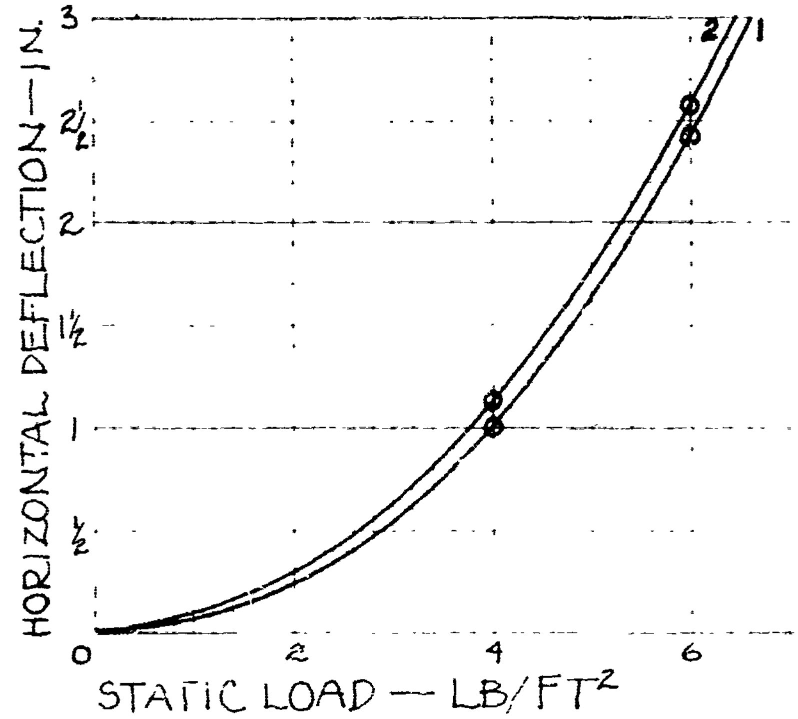


TABLE V - HORIZONTAL DEFLECTION TEST - FOME-COR TEST ARCH ("BOW-TIE" CONCEPT)

TEST DESCRIPTION (TABLES IV & V)

One complete modular arch (see sketch) constructed of 1/4" Fome-Cor and reinforced with 1" galvanized steel channels and aluminum gusset plates was tested by the application of a gradually increasing uniformly distributed load. As the loading approached $8\#/ft^2$ two of the bow-tie units located at the base indicated buckling failures at the central joints. Uneven deflections apparently forced one portion of the unit out of line with the other producing a small couple which caused the gusset plate to buckle and the board to deform. It seems unlikely that this type of failure could occur in the completed structure. However, the reinforcing in this area was improved by extending the gusset plates to the bottom edge so that the channels overlap the gusset plates, by extending the channel length so that they butt end-to-end, and by designing the clips with washers with protruding tips to grip the panel board.

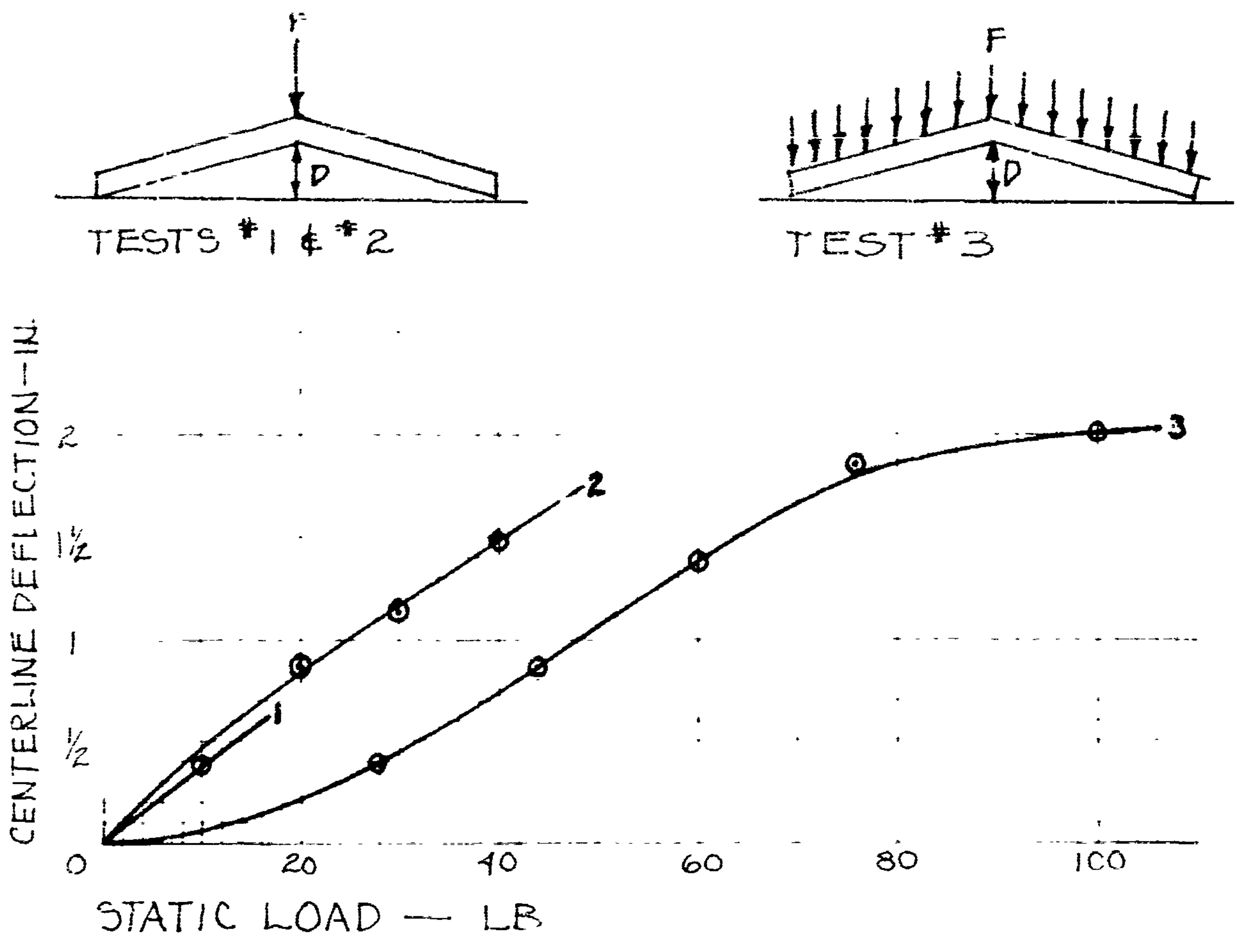


TABLE VI - STATIC LOAD TESTS OF TECHNI-FOAM "BOW-TIE" MODULES

TEST DESCRIPTION

TEST #1 - One modular unit constructed of 1/4" Techni-Foam and reinforced with 1" galvanized steel edge channels and nylon reinforced paper tape at the center joint was subjected to a gradually increasing concentrated load at the center ( ). The panel failed in tension at the bottom edge of the center point.

TEST #2 - The modular unit was reinforced at the center with galvanized steel gusset plates and loaded as in Test #1. The panel failed by compression and buckling at the ends of the gusset plate at the point where the load platform rested on the panel.

TEST #3 - The modular unit described in Test #2 was subjected to a gradually increasing uniformly distributed load. As the load increased beyond 10#/ft^2 there was excessive deflection but no indication of structural failure. The panel was not tested to destruction.

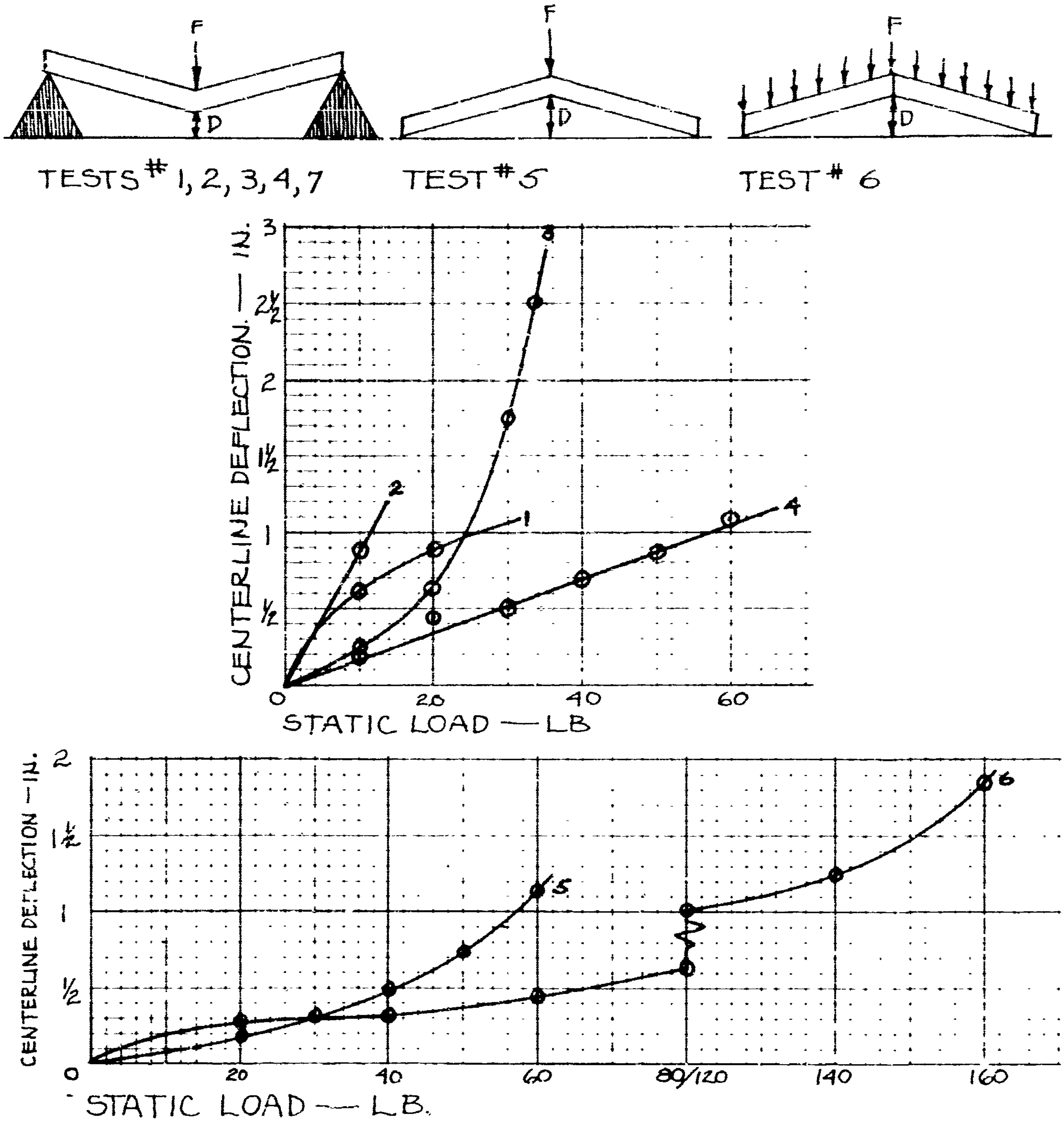


TABLE VII - STATIC LOAD TESTS OF FOME-COR "BOW-TIE" MODULES

TEST DESCRIPTION

TEST #1 - One modular unit constructed of 1/4" Fome-Cor reinforced with 1" galvanized steel edge channels and nylon reinforced paper tape at the center joint was subjected to a gradually increasing concentrated load at the center. The panel failed by buckling at the top edge of the center joint.

TEST #2 - The modular unit described in Test #1 was modified by butting the edge channels end-to-end at the center joint. This test was inconclusive since the channels slipped.

TEST #3 - Test #2 was repeated with channels crimped more securely to the board. The model failed in tension at the bottom edge of the center joint.

TEST #4 - The modular unit of the previous tests was further reinforced by adding aluminum gusset plates at the center. These plates were extended to the panel edge so that the channels overlapped them. The plates were adhered with contact cement and the channels with Elmer's glue. Although the load was doubled there was no failure and deflection was only 45% of that observed in Test #3.

TEST #5 - The modular unit of Test #4 was inverted and tested to failure. It failed by buckling of the gusset plates.

TEST #6 - The modular unit of Test #5 was subjected to a gradually increasing uniformly distributed load. Failure finally occurred by buckling at the ends of the gusset plates. Excessive deflection was due largely to compression in the board at the ends of the unit.

TEST #7 - The same modular unit used in Tests #4, #5, #6 was inverted and subjected to a gradually increasing concentrated load at the center. Failure occurred by buckling of the edge channels. This test was considered inconclusive since the same unit tested in #4, #5, and #6 was used.

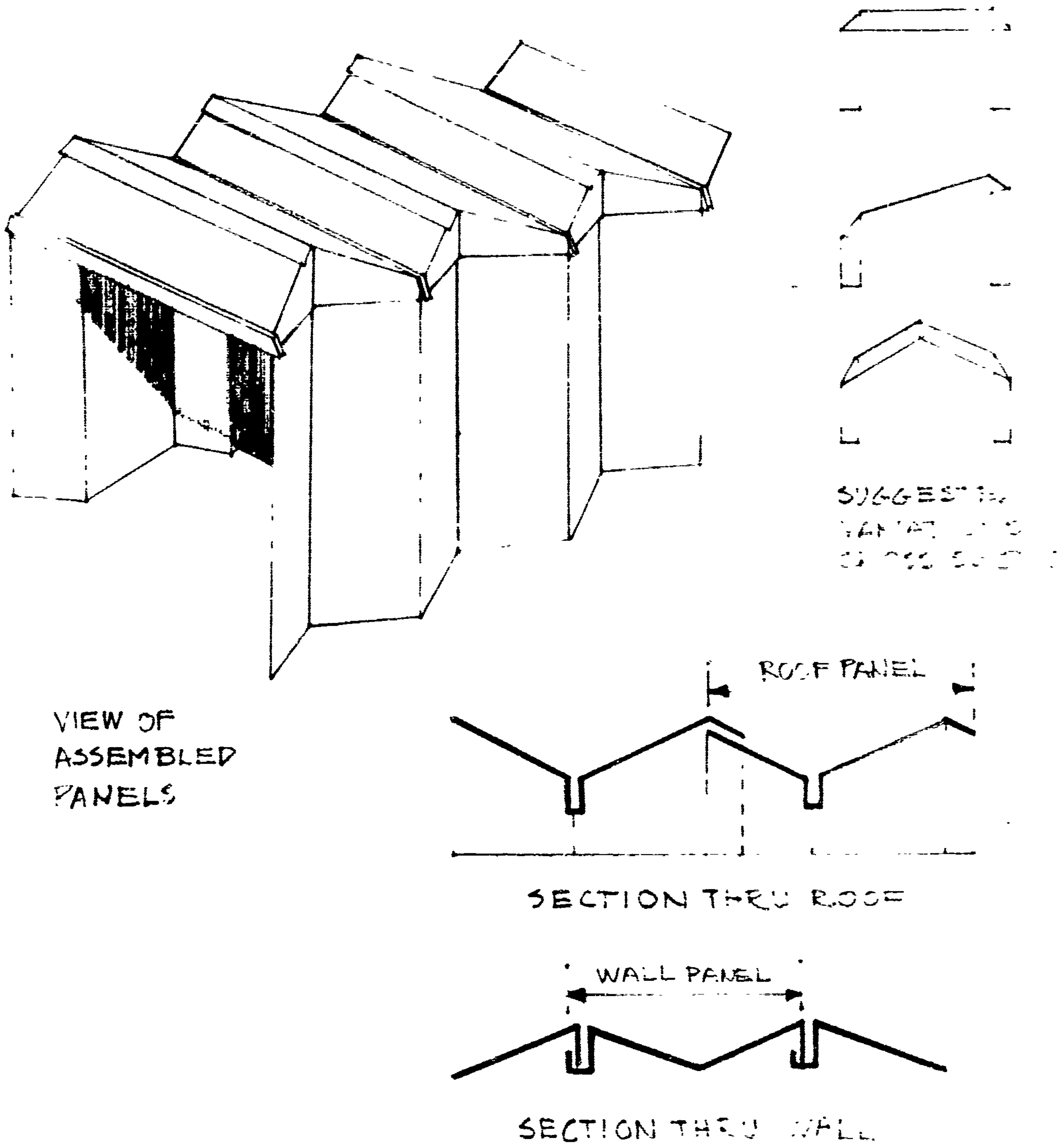


FIGURE 6. BELLOWS CONCEPT

impregnations would have added to the attractiveness of these materials. From standpoints of weight/strength ratio, ease of scoring and folding, and insulation value, these materials seemed less desirable than the foam sandwich materials.

(2) U.S. Rubber expanded "Royalite" indicated that a very durable, almost permanent, structure could be made of this product if used in the "bow-tie" concept. The panel would have to be molded in final form thus presenting problems of stocking or packaging the products for shipping. Expanded Royalite could be considered for a rigid floor system if this were ever considered a requirement.

(3) MR Board with styrofoam filler and .080 Pan-L liners as manufactured by Morton Rand Corp., Zanesville, Ohio. This material was found to be very strong and, with proper applied finishes, wear and weather-resistant. The .080" thick Pan-L liners made the material quite heavy. It was felt that in 1" or 1 1/2" thicknesses the material had possible uses as doors or in rigid floor and packaging systems.

c.) Domical configurations

Existing geodesic dome panelized examples built and tested by Monsanto at St. Louis and Mead at Chillicothe, Ohio gave good indications as to the weatherability of Fome-Cor in the Monsanto structure and corrugated fiberboard in the Mead structure. For reasons stated earlier, the dome configuration did not seem applicable to the problem here.

d.) Exterior finishes

Extensive work was done by the Archer-Daniels-Midland Company in preparing a two-part epoxy type coating utilizing their Aroflint 505 system. A test "bow-tie" module was painted with two coats and weather tested for three weeks. While the finish itself performed satisfactorily, the test demonstrated the importance of protecting the edges of foam board from weather and the necessity of having identical finishes on interior and exterior surfaces to minimize warpage. Samples of Fome-Cor with two coats of Aroflint 505 on each face successfully passed a 200-hour test in ADM's National XlA Weatherometer.

e.) Weatherseal gasketing

Several types of closed cell neoprene gasketing (both with and without skin) were obtained and tested for water permeability, compressibility, and recovery after compressing. Types obtained were manufactured by Rubatex Corp., Radford, Virginia.

C. CONSTRUCTION OF SMALL SHELTER #1

As the structural tests described in paragraph B-4 were being conducted, this contractor (under an amendment to the contract) was directed to construct a full-size shelter employing the modular "bow-tie" concept as developed in the preceding studies.

The structure was to be designed, constructed, test-erected, packaged, and shipped to an Air Force base for field test in less than eight weeks after the directive was received.

Dimensions specified for Shelter #1 were 38' long by 16' wide. A large 8' door was called for in one end, a small one at the other end, and ventilating windows were to be provided in ten modules. Grade beams and a flooring material were to be supplied.

All components for Shelter #1 were built, fabricated, and/or assembled by the research group at the college during the months of July and August, 1964. It was delivered for field testing on September 1. Following is an abbreviated description of the various components and elements of the design:

Structure: folded "bow-tie" modules of 1/4" Fome-Cor reinforced with .020 aluminum edge channel, "chevron" reinforcement at waist, washers at connectors.

Connectors: thumbscrews, wingnuts, and washers; strap steel and wingnut stirrups and washers at bow-tie waists.

End treatment: identical folded Fome-Cor side panels and gable pieces at each end framing 8' wide x 6'10" high opening.

End opening options: (a) 1 double door filling 8' x 6'10" opening, door material: 1-1/2" thick MR board (Morton Rand Company), door frame: wood head and jambs (shipped K.D.). (b) three interchangeable units to fit within 8' x 6'10" opening: single 2'10" x 6'10" x 1 1/2" thick door preassembled in wood frame, 2'10" x 6'10" Fome-Cor blank filler panel, and 2'10" x 6'10" Fome-Cor panel containing screened ventilating openings with top-hinged protective shutter.

Exterior and interior protective finish: two coats epoxy-type Aroflint 505 paint (Archer-Daniels-Midland). Exterior color: light olive, interior color: off-white.

Weather seal between modules: 1/4" x 1 1/4" strips closed-cell neoprene sponge attached to ribs below fold line on "bow-tie" modules, 3/8" neoprene "doughnuts" on strap stirrups at joint intersections.

Windows: triangular cutouts in Fome-Cor, screened on inside, top hinged protective shutter, operating rod.

Grade beams: 4 1/2" x 7" hollow wood sections made of plywood and 2 x 4's connected by 4 x 4 "tongues" locked into place by 1/2" carriage bolts dropped into prepared holes.

Floor covering: Neoprene coated nylon-mesh tarpaulin.

In three areas the pressure of schedule forced adoption of details that should, time permitting, have been developed further: (1) grade beam could have been much lighter in weight probably aluminum. (2) neoprene weatherseal gave indications of not being completely effective largely because of the lack of uniform pressure along joints between modules inherent in the use of point, as opposed to linear, connections, and (3) thumbscrew/wingnut connector installation was time consuming.

Weight of the 16' x 38' shelter (less wood grade beams, stakes, tarpaulin and plywood upper package) was 837 lbs.

Figure 7 shows the plan, elevation, and module drawings of the "bow-tie" concept, and Figure 8 is a rendering of the exterior of the erected shelter. Figure 9 shows in sketch form how, with modifications, the concept could be utilized in creating expanded L, T, U, and H type buildings. The completed shelter #1 is shown in Figure 10 as erected in the University Field House prior to delivery for field testing. An interior view is shown in Figure 11. Figure 19 shows a rendering of a shelter adapted for use as a mess hall.

D. FIELD TESTING OF SMALL SHELTER #1

On 1 September, 1964 Shelter #1 was air lifted aboard a C-130 type aircraft to Eglin AF Base. The package size of the single package was 4'9" wide x 10'0" long x 5'6" high (approximately 261 cu ft).

On 2 September the shelter was erected in the field where it was to serve as a command post/briefing room during Indian River III exercise. Unpacking and erecting was accomplished by a five-man university team in approximately six hours (30 man hours) in temperatures reaching 103° F. For this test the Air Force had provided a plywood floor made of standard 4' x 8' tent flooring panels.

The shelter remained in place until it was dismantled on 17 September. During this period an upper class co-op student from the college remained at the field exercise as test monitor.

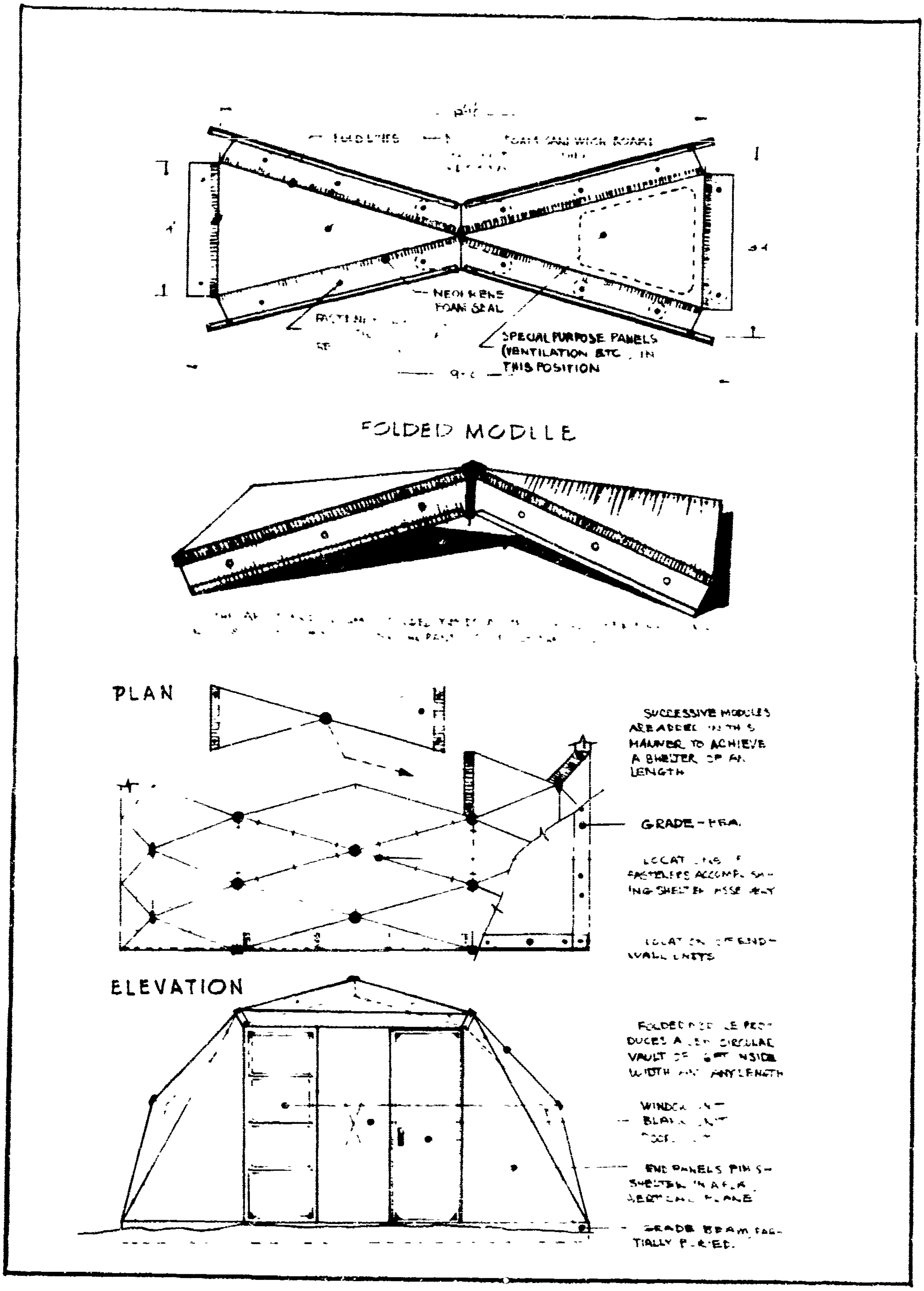


FIGURE 7. PLAN, ELEVATION, AND MODULE DRAWINGS ("BOW-TIE" CONCEPT)

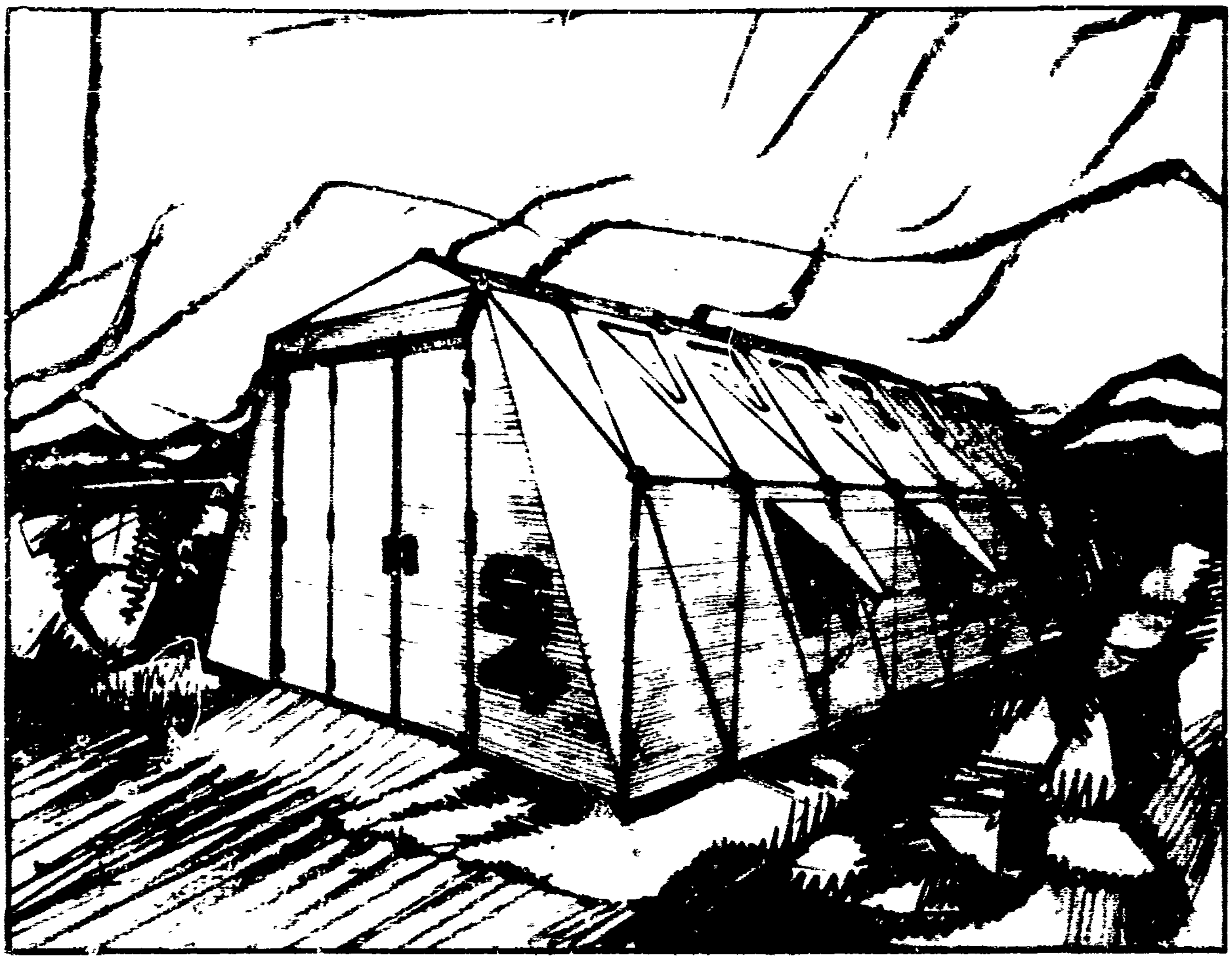


FIGURE 8. RENDERING OF SHELTER USING "BOW-TIE" MODULE
(SHELTER SHOWN APPROXIMATELY 20 FT LONG)

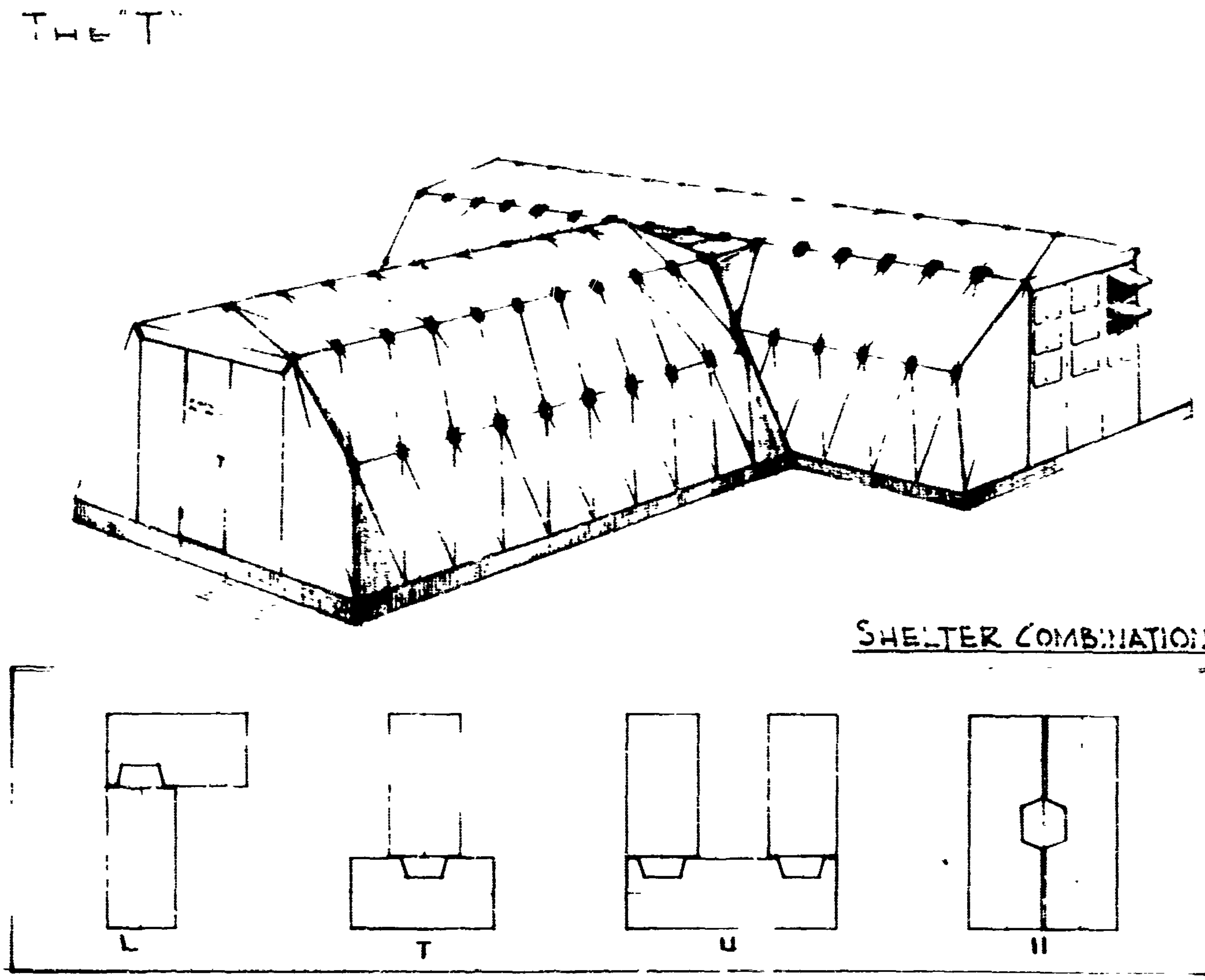


FIGURE 9. TECHNIQUES OF JOINING "BOW-TIE" UNITS TO MAKE MULTIPLE UNIT SHELTERS

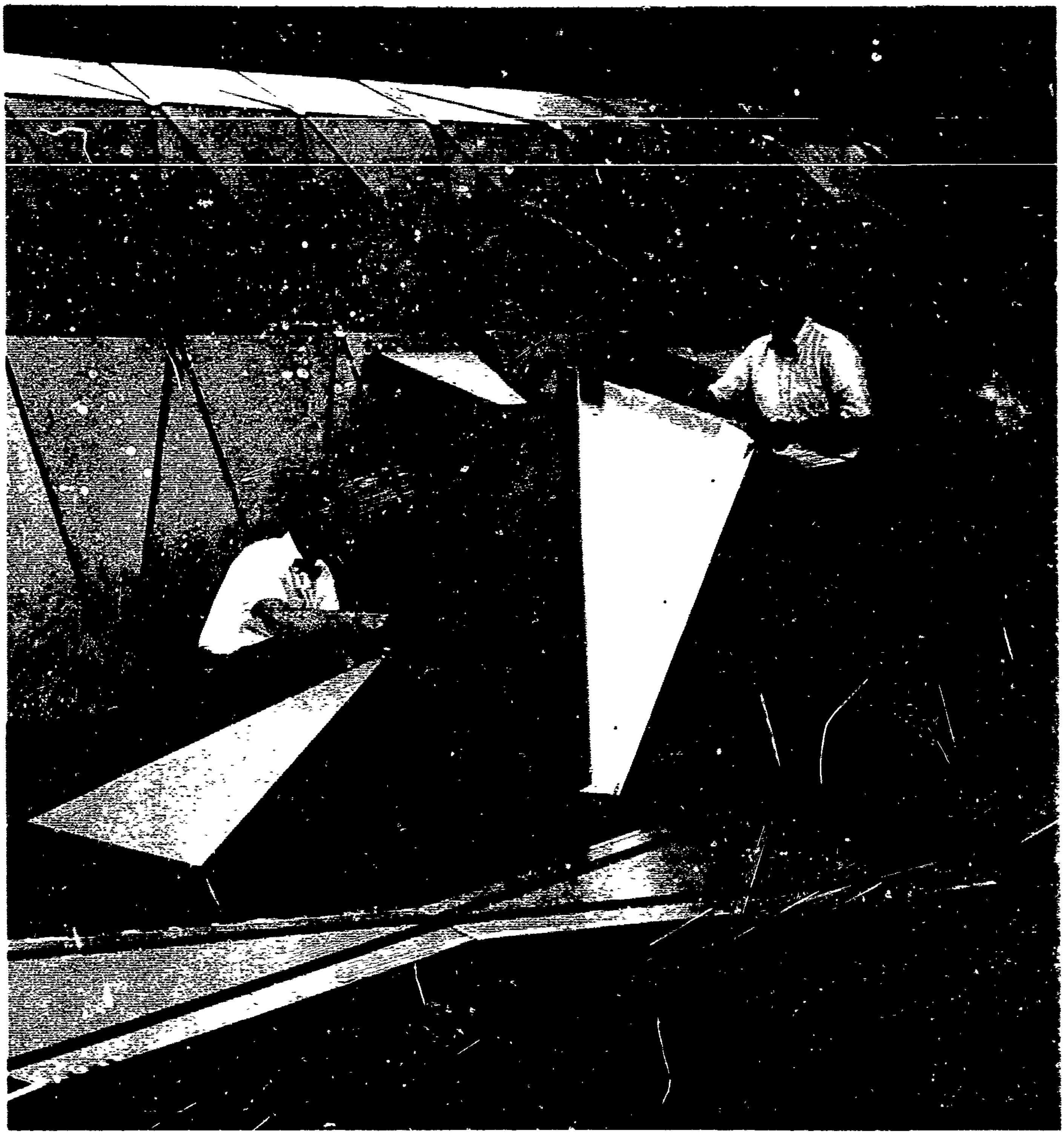


FIGURE 10. SHELTER #1 - TEST ERECTION AT UNIVERSITY OF CINCINNATI FIELDHOUSE/ARMORY

FIGURE 11. SHELTER #1 - INTERIOR VIEW

Severe weather was experienced during the test. On two occasions winds reached 40 knots. For several days during the period the camp was evacuated in anticipation of being struck by hurricane Dora. Though the hurricane missed the site, tropical storms with sustained winds of 25 knots and rainfall accumulations of over two inches per day were experienced for several days. Though all personnel was evacuated and conventional tentage struck during the alert, the shelter remained in position.

From a structural point of view the shelter performed admirably. At the height of the first 40 knot gusts, only a very slight tremor could be detected by feel. At this time the auxiliary rope tiedowns were not in place, the shelter being anchored only by grade beam stakes. Subsequently the auxiliary rope tiedowns were installed.

Considerable leakage was experienced. As anticipated the uneven pressure on gasketing allowed some water to enter. Also the neoprene sponge "doughnut" on the stirrup connectors did not adequately seal the intersection of modules and the water tended to drip down the connector and hence to the floor. On the third day of the test tape was applied to the exterior of joints. This controlled leakage so that the shelter could be used as an office and briefing room by General Delashaw.

Wiring and fluorescent lights were installed by suspending them from the connectors along the ridge of the shelter. The off-white interior surface of the shelter provided good reflectivity.

Two unit air conditioners were installed in the shelter, one at each end. With outdoor temperature readings of 88° f, inside thermometers read 80°.

On 17 September a five-man crew (three from University of Cincinnati, two from Air Force) disassembled and repackaged the shelter in approximately five hours (25 man hours). The packaged shelter was air-lifted via C-130 to Wright Patterson AF Base on 18 September and was subsequently returned to the campus via truck.

Summarizing the observations on the field test:

(1) Structural design proved completely adequate.

(2) Fome-Cor material performed satisfactorily and all components came through the test undamaged.

(3) Paint provided satisfactory protection for Fome-Cor. Choice of medium high gloss finish was questioned as it was easily detected from air.

(4) Design goals for further studies were:

a.) more effective sealing against leakage

b.) reduction of weight by use of lighter weight grade beam

c.) more rapid erection time by employing a less time-consuming connector than the thumbscrew/wingnut one

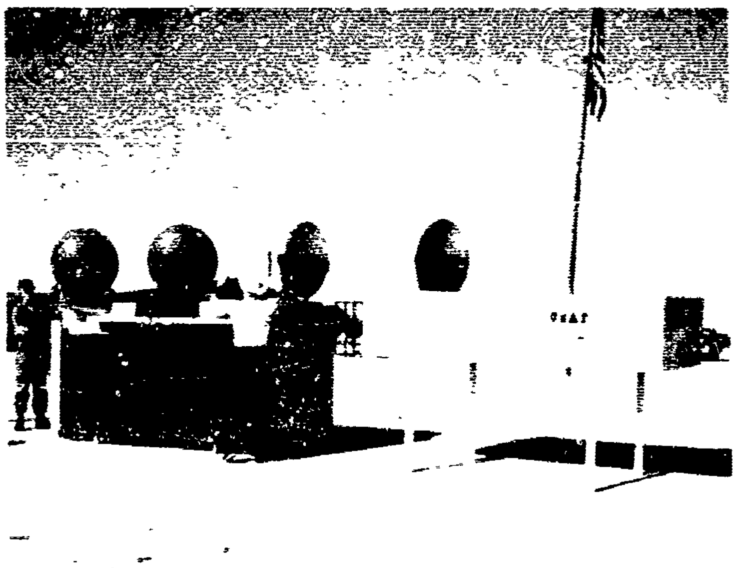
d.) reduce amount of unprotected ferrous metal (evidence of rusting of connectors was noted)

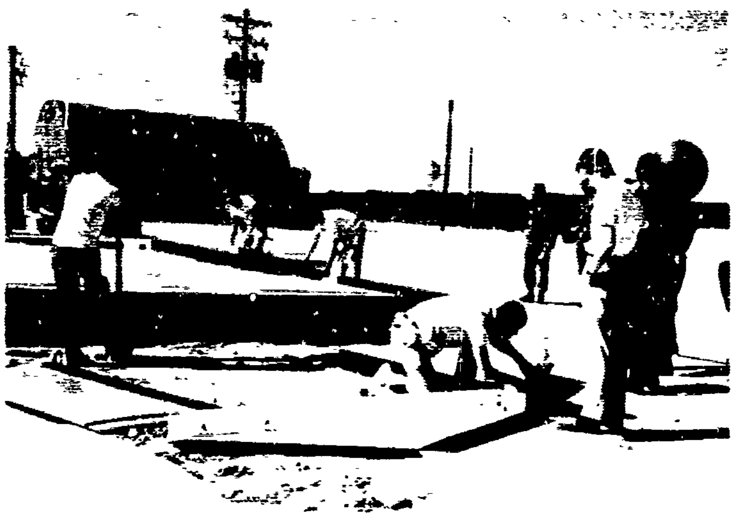
e.) reduce reflectivity and make structure less conspicuous from air observation by using a low-gloss olive-drab exterior finish.

Photographs taken during the field test at Eglin AFB are shown in Figures 12 through 16.

Upon return of Shelter #1 to the university campus, a shortened version (approximately 20 feet long) was erected outdoors and remained there for approximately ten months. No deterioration of material or finish has been detected during this period. Figure 17 shows this shelter during a five-inch snow in midwinter 1964-65.

An artist's concept of this shelter adapted for use as a mess hall is shown in Figure 19.





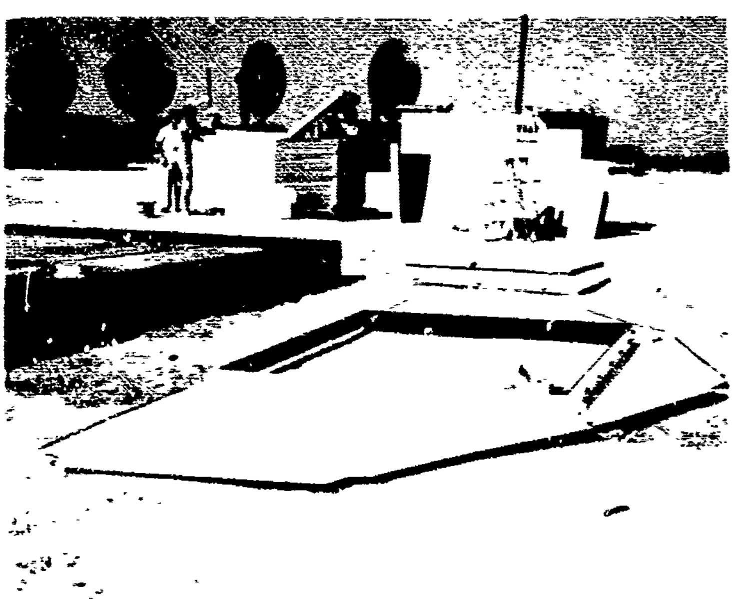


FIGURE 12. SHELTER #1 - EGLIN AFB FIELD TEST (UNPACKING, SETTING GRADE BEAM, AND ASSEMBLING END OF SHELTER)

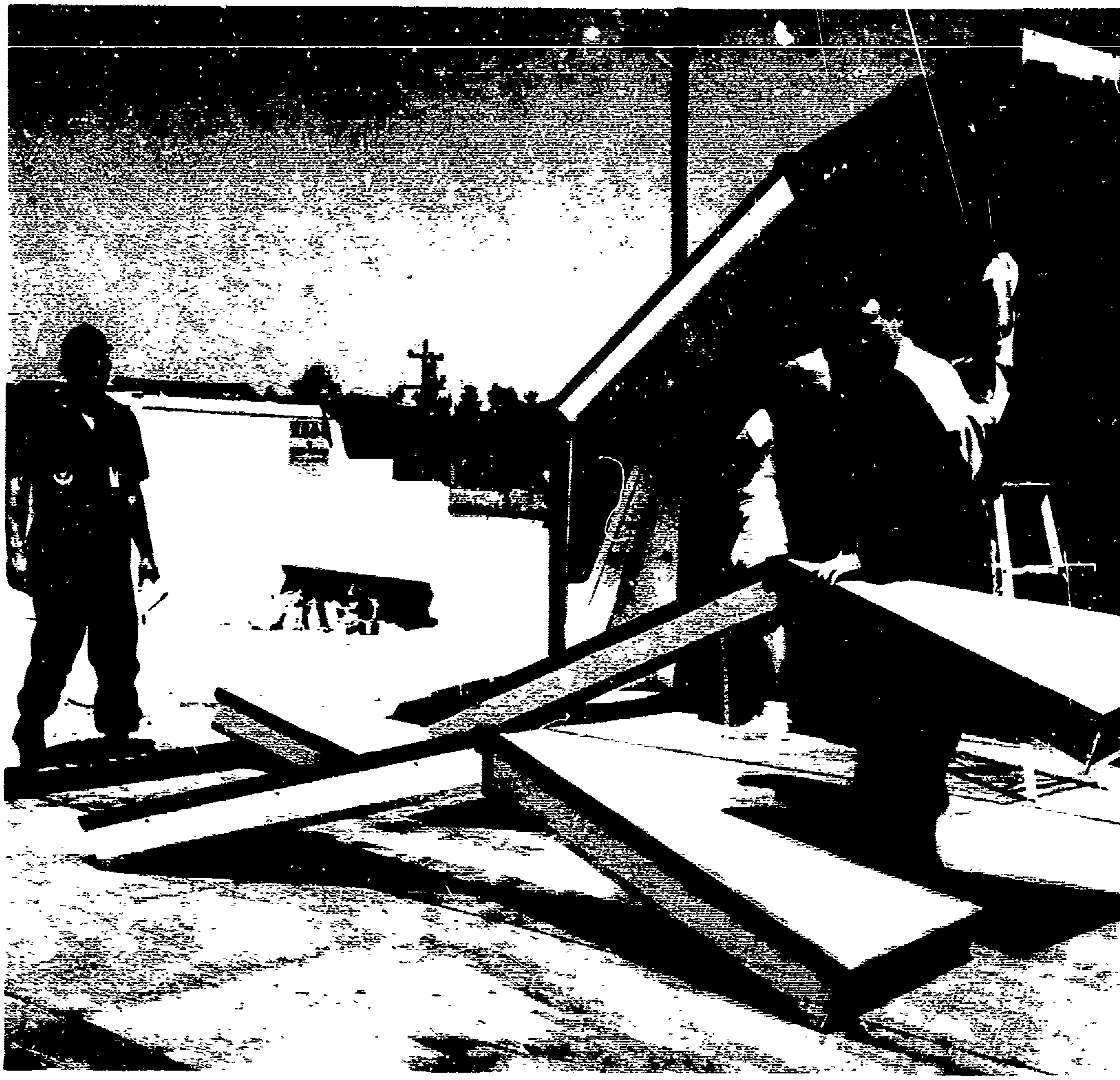


FIGURE 13. SHELTER #1: FOLDED "BOW-TIE" MODULES READY FOR INSTALLATION

FIGURE 14. SHELTER #1: ASSEMBLY OF "BOW-TIE" MODULES AND END

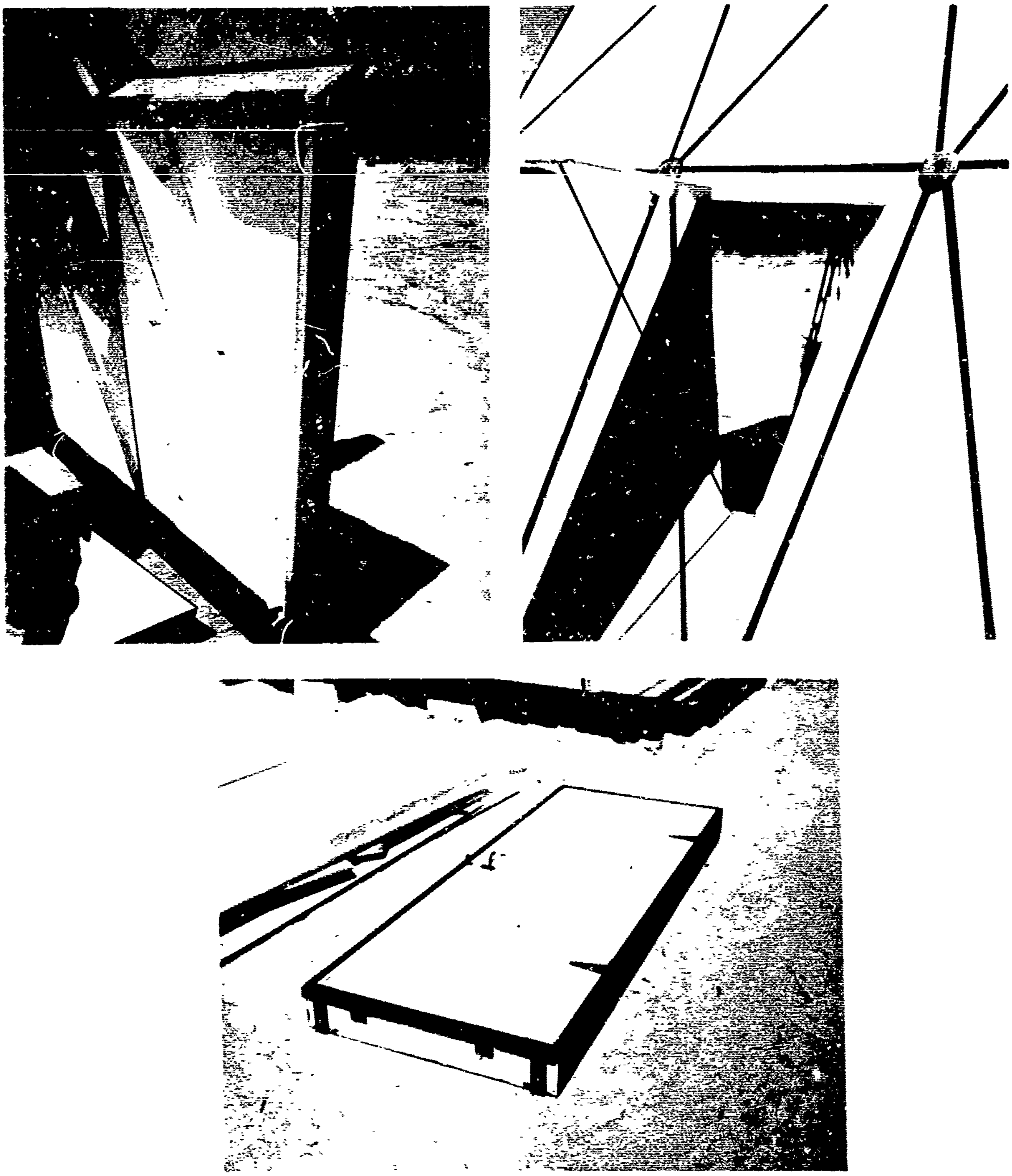
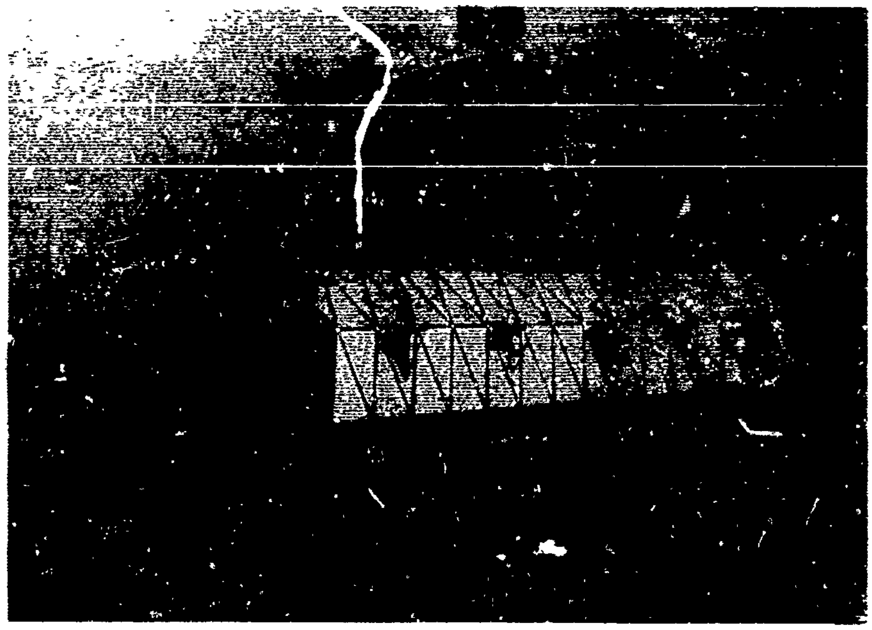


FIGURE 15. SHELTER #1: DETAILS (HALF MODULE IN PLACE, WINDOW DETAIL, PREHUNG DOOR IN WOOD FRAME)



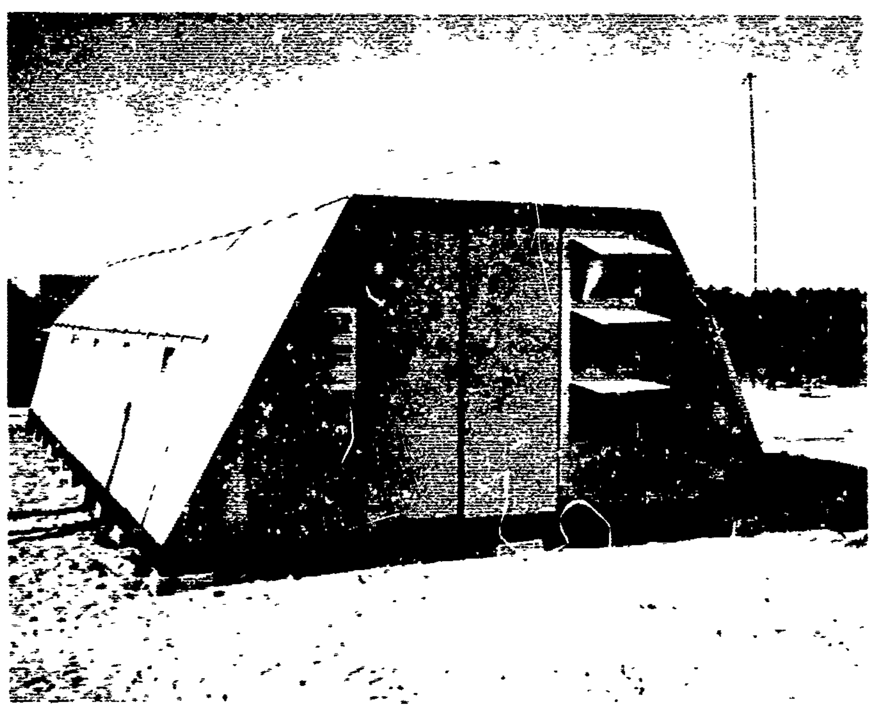


FIGURE 16. COMPLETED SHELTER #1

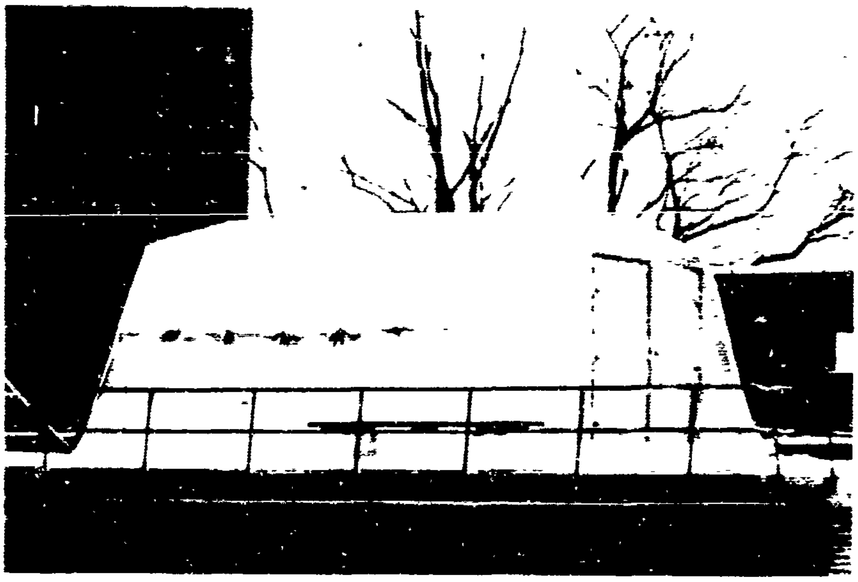


FIGURE 17. SHELTER #1: SNOW LOAD TEST AT UNIVERSITY OF CINCINNATI, FEBRUARY 1965

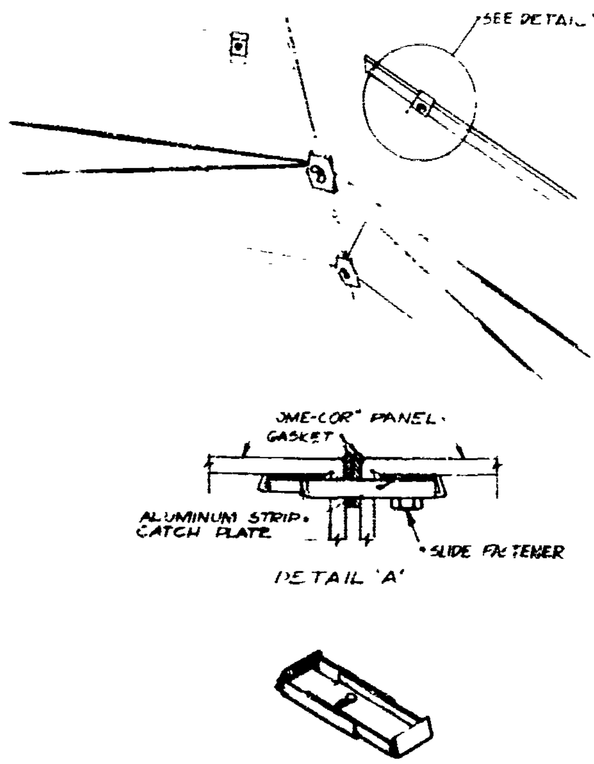


FIGURE 18. SHELTER #1: PROPOSED IMPROVED CONNECTOR CONCEPTS

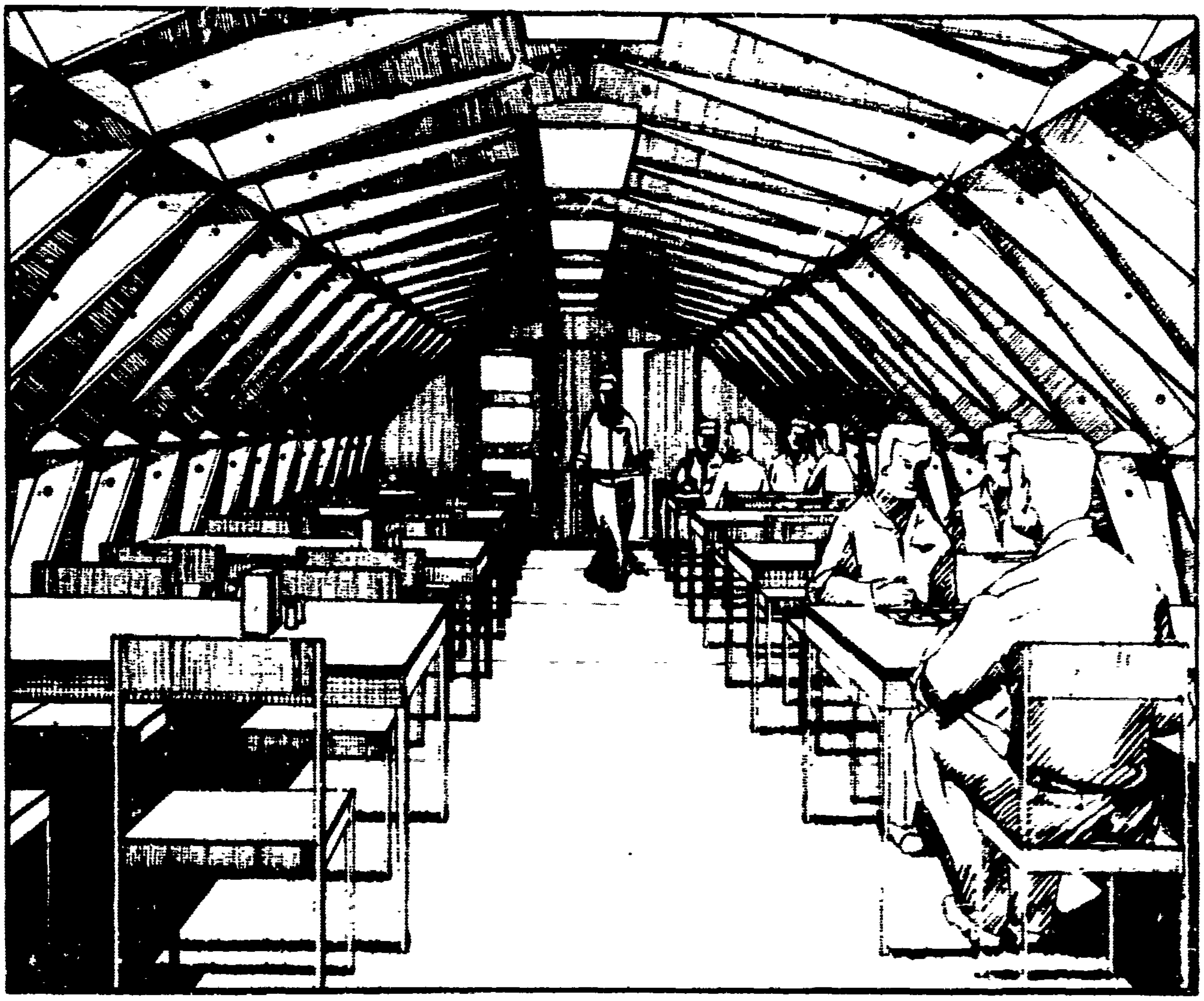


FIGURE 19. SHELTER #1: RENDERING (POSSIBLE USE AS A MESS HALL)

As subsequent changes in design were adopted, the prototype of Shelter #1 became less central to the continuing study, and in late July, 1965 it was flown to El Centro, California where it has been erected at the El Centro Navy Base and is serving a useful life in this desired climate. A checklist covering performance is being maintained at the El Centro installation and periodic reports will be submitted.

E. PROPOSED IMPROVEMENTS ON "BOW-TIE" CONCEPT

In line with the design goals stated following the Eglin field test, two steps were taken toward improving the "bow-tie" concept:

(1) A formed aluminum grade beam of section configuration was designed and sample sections procured. Substitution of this grade beam for the heavy wood one would result in great weight saving.

(2) An eccentric cam-type connector was designed utilizing and modifying an existing Simmons connector and a number of them were fabricated. Figure 18 shows the connector and its proposed use.

(3) Samples of plastic and rubber gaskets of several different sections and composition were obtained from the Jarrow Products Company and studies were begun on methods of applying them to the problem of improving weather-sealing capabilities.

Concurrent studies of an alternate concept had begun and showed promise so further work on the "bow-tie" concept was set aside.

F. "FOLDED DIAMOND" MODULAR CONCEPT

This concept was based on a folded plate formed from a rectangular flat sheet of 1/4-inch thick Fome-Cor. Less waste of the sheet material resulted from the adoption of a rectangular module. Three of these rectangular modules were taped together so that, when unfolded and formed along previously scored lines, one complete arch could be created. In terms of numbers of separate pieces to be handled in erection, this approach meant that fifteen such arches would cover the same area as the ninety-six "bow-tie" modules (in a 38' long shelter).

Figure 20 shows a rendering of a 30' long shelter employing this concept.

Strength is obtained by scoring "bow-tie" shapes on the rectangular modules and folding them during erection so as to form triangular prisms resulting, when assembled into a shelter, in a series of diamond shapes in two planes.

A preliminary full-size triple arch in corrugated fiberboard was constructed to verify the basic geometry (See Figure 22). Figure 21 illustrates basic elevation views and the basic module/arch drawings. It shows a further refinement involving stand-up ribs at joints, metal-reinforced and treated-fabric diaphragm-covered origice at the center of the module, and fabric tie-straps utilizing Velcro nylon fasteners. The folds are so arranged that the inward folded prisms overlap to form self-flashing gutters. Continuous connector-flashing tape fits snugly over the standing ribs.

A three-arch section test vault was constructed next. One-quarter inch Fome-Cor was used for the panels with hinges made of Tedlar tape. An improved lightweight aluminum grade beam was designed but was not available for this test. The test arch was loaded to 8 lbs per square foot. Failure occurred at this loading. This was deemed encouraging considering the saving of material of this concept over the "bow-tie" concept. It was noted, however, that prior to failure, deflection at the ridge was 4 3/4" as compared with the 1 13/16" deflection on the "bow-tie" arch under the same loading. Failure occurred when the upright ribs buckled at the first hinge point above the grade beam.

Test results are plotted on Tables VIII and IX, and the testing is shown in Figure 23.

Some study was made relative to stiffening of the upright flanges by inserting horizontal braces between them. An alternate study involved the turning of the flanges inward and folding them into triangular box beams. This last study led directly to the evolution of the current concept, the "folded beam" concept.

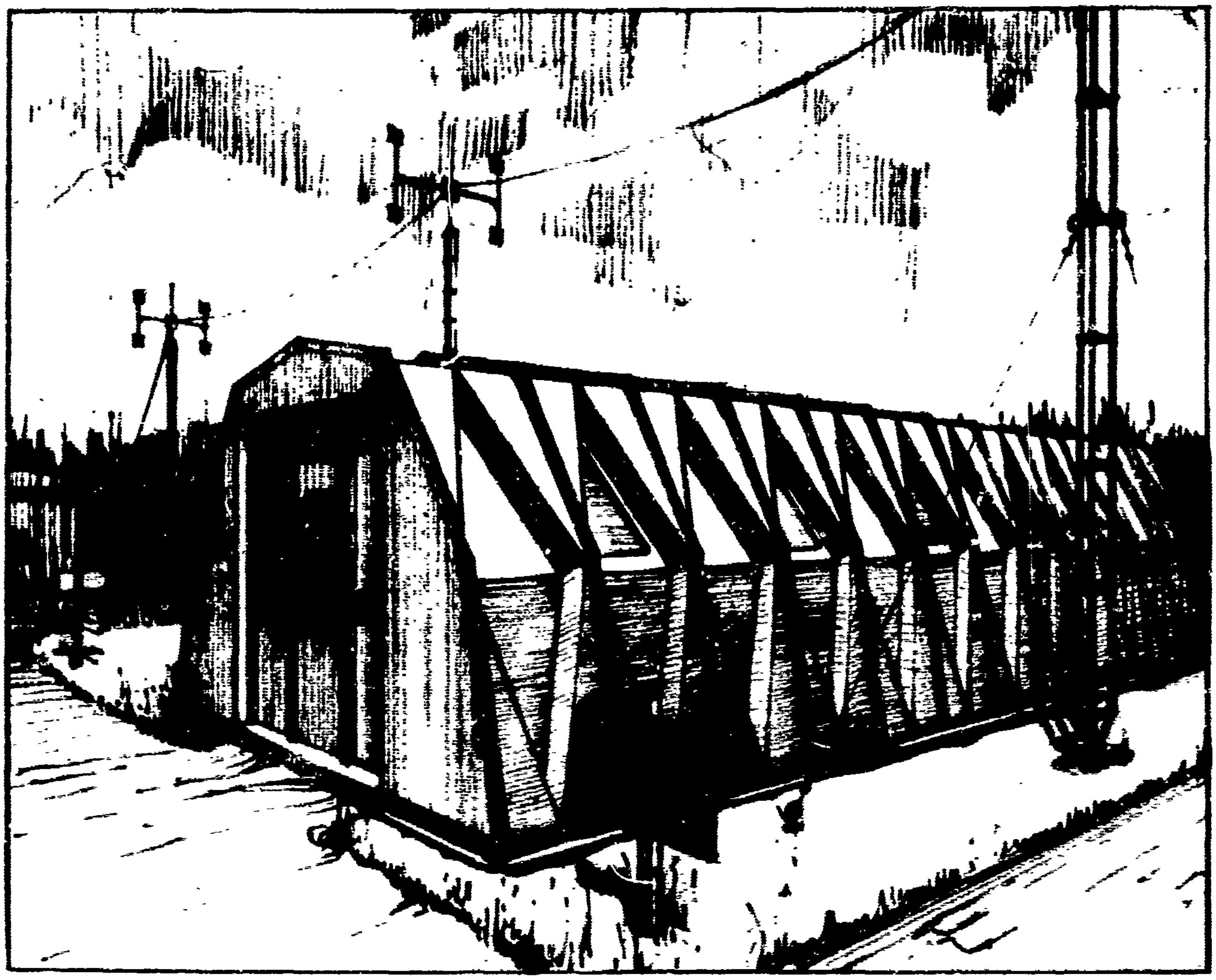


FIGURE 20. RENDERING OF SHELTER USING "FOLDED DIAMOND" CONCEPT

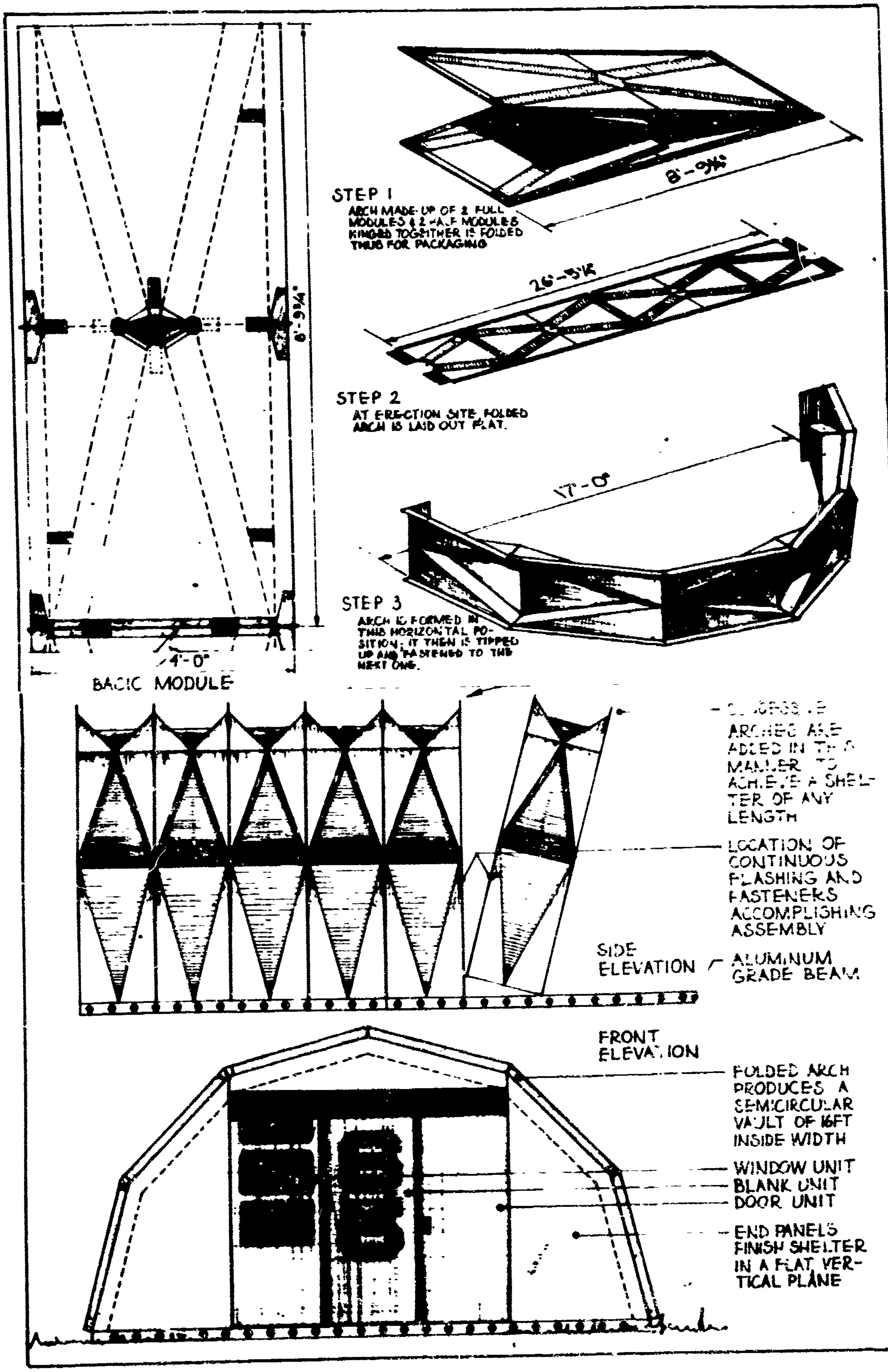


FIGURE 21. ELEVATIONS AND BASIC MODULE/ARCH DRAWINGS ("FOLDED DIAMOND" CONCEPT)

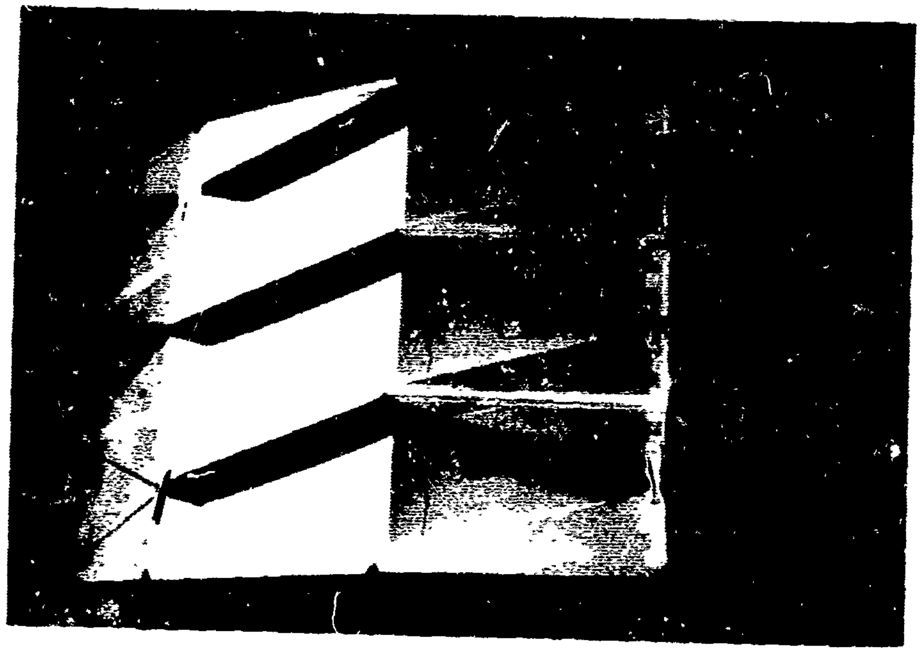
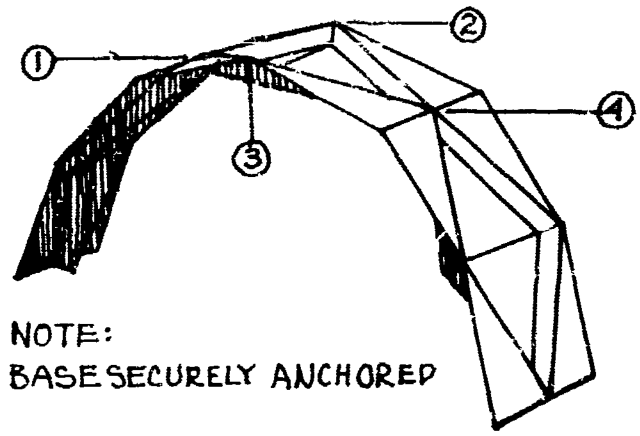
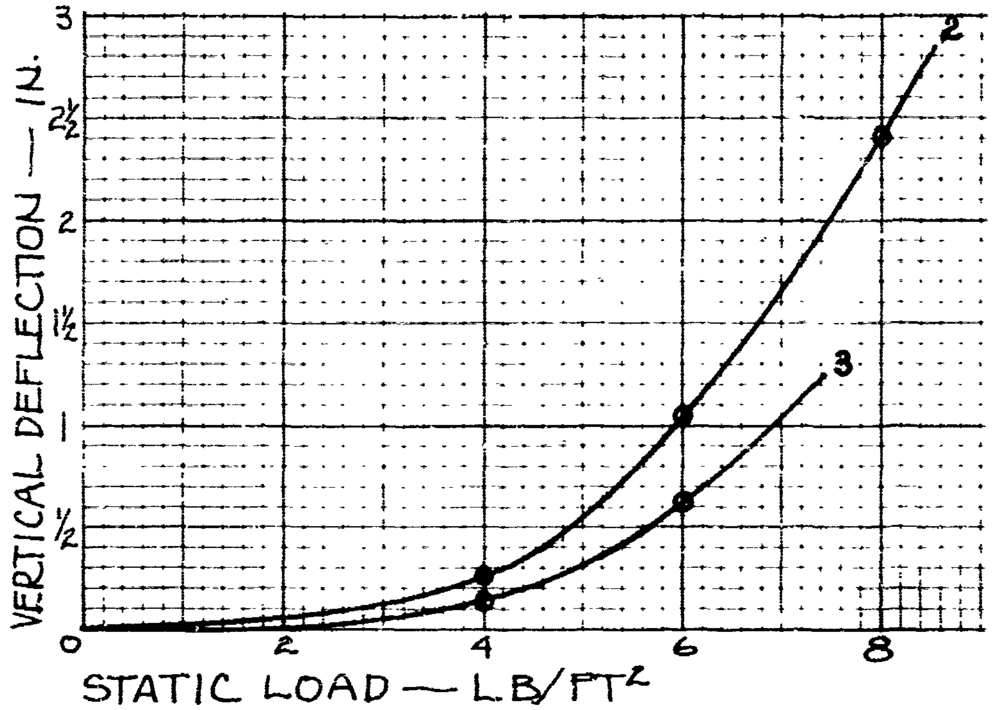


FIGURE 22. "FOLDED DIAMOND" TEST ARCH, VIEW FROM ABOVE

FIGURE 23. TEST ARCH UNDERGOING STATIC LOAD TESTING ("FOLDED DIAMOND" CONCEPT)





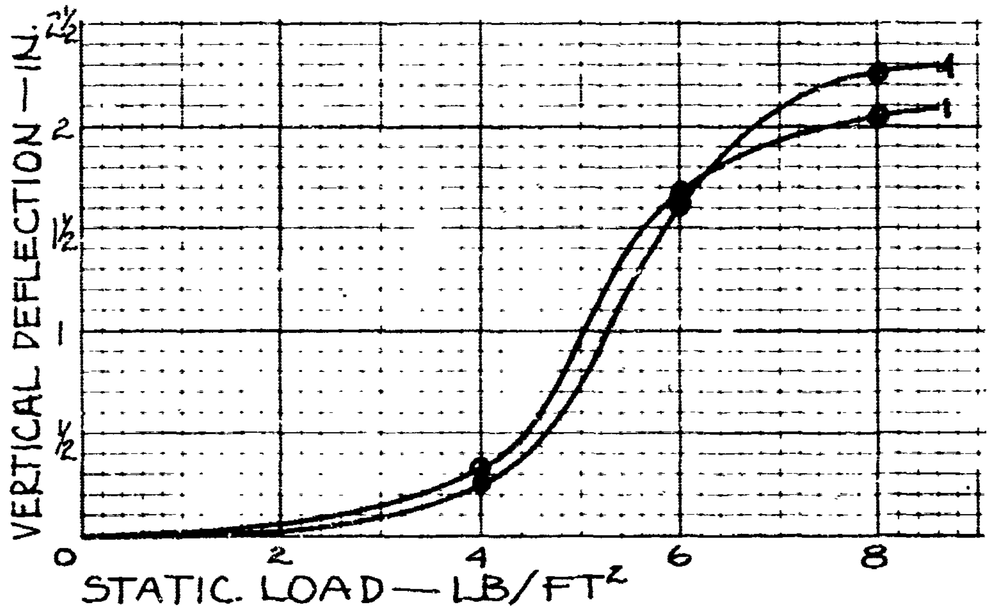


TABLE VIII - VERTICAL DEFLECTION TEST - FOME-COR TEST ARCH ("FOLDED DIAMOND" CONCEPT)

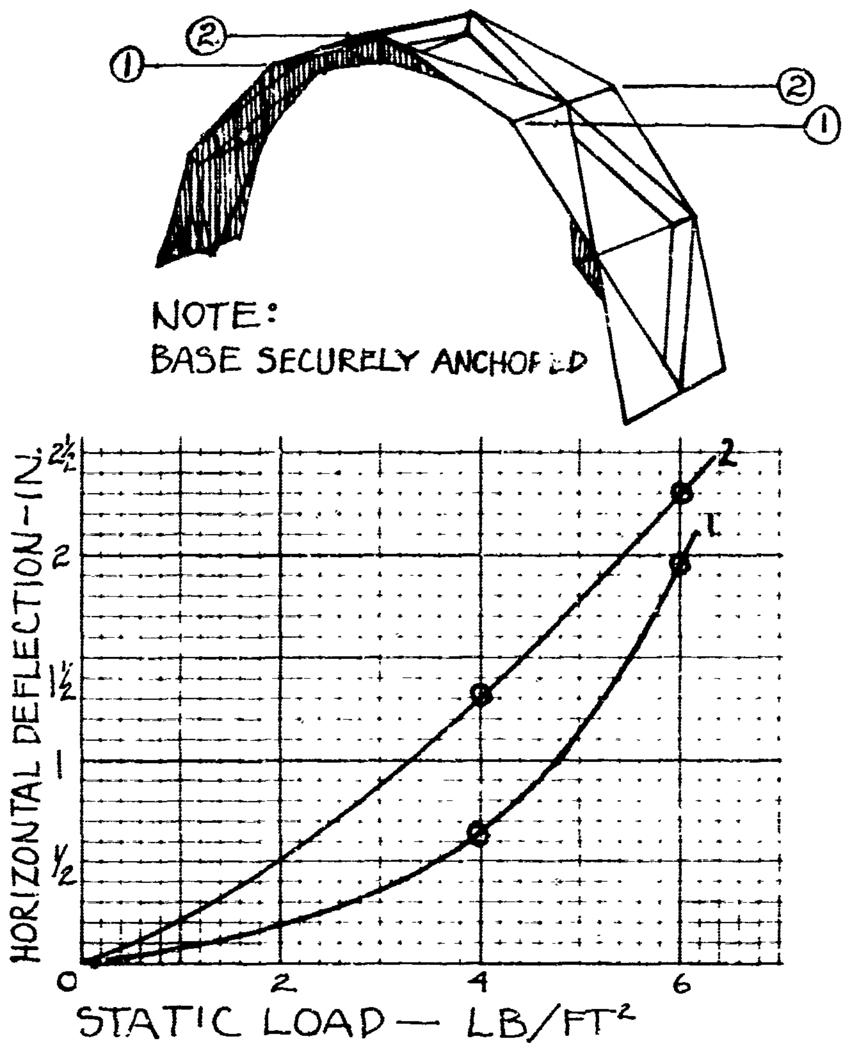


TABLE IX - HORIZONTAL DEFLECTION TEST - FOME-COR TEST ARCH ("FOLDED DIAMOND" CONCEPT)

TEST DESCRIPTION (TABLES VIII & IX)

A three-arch section constructed from 1/4" Fome-Cor was tested by gradually increasing uniformly distributed load on the center module. As the loading reached 8#/ft^2 failure occurred when the upright ribs buckled at the first hinge point above the grade beam.

In summary, the "folded diamond" concept represented a step forward in the areas of economy of material and reduction of numbers of components handled in the field. On the negative-side, the concept did present a fairly complex on-the-site folding operation for an untrained erection crew. In the final development stage, the manufacture of the orifice at the center of the module (with its metal reinforcing, waterproof diaphragm, and self-flashing gutter features) seemed to be overly complex and sophisticated. A final drawback to any approach characterized by the alternating planes of the folded prisms is the difficulty of applying additional insulation when needed.

G. "FOLDED BEAM" MODULAR CONCEPT

This concept grew out of two things: (1) the aforementioned proposed triangular section rib or beam for the "folded diamond" concept, and (2) the research into adhesives, flexible attachment devices, and coated fabrics undertaken in connection with the previous concept. In this concept all diagonal folds or rib patterns were abandoned, and a straight-forward parallel rib pattern was adopted.

As in the previous concept, a typical arch was formed by hinging together with Tedlar tape three rectangular panels each 4 ft wide by approximately 9 ft long. Each panel was scored and tape-reinforced at midpoint thus creating a six-chord arch. The outboard 12-inch wide quarters of the 4 ft wide modules were scored so that, when folded, rigid triangular-section beams were formed. Each beam is held in its folded position by means of previously attached "beam hold-down" webbing tabs with Velcro nylon fastener aligned so that hook engages pile when the beam is folded.

A typical arch is formed by following the four steps shown in Figure 24. For reinforcement in compression and for alignment in folding the segments into the arch, tongue and grooved lightweight aluminum channels cover the edges of the diamond-shaped openings in the module (See Figure 24). Tensile strength at these angles is obtained by cross-over webbing straps with Velcro "hook" patches that attach to properly placed "pile" patches on the appropriate beam face surfaces.

Velcro is also used in attaching adjacent arches to each other. This is done both internally and externally. Inside the shelter cross-over straps with Velcro patches lace adjacent beams together. Externally a broad band of neoprene-coated nylon is permanently glued to one edge of the arch and is secured in erection to the adjacent arch by means of continuous Velcro "hook" strip on the flashing being pressed into a continuous strip of "pile" Velcro on the mating edge of the adjacent arch. The flashing also spans a compressible foam-filled neoprene gasket strip that parallels the Velcro "pile" strip. This assures a leakproof joint in use.

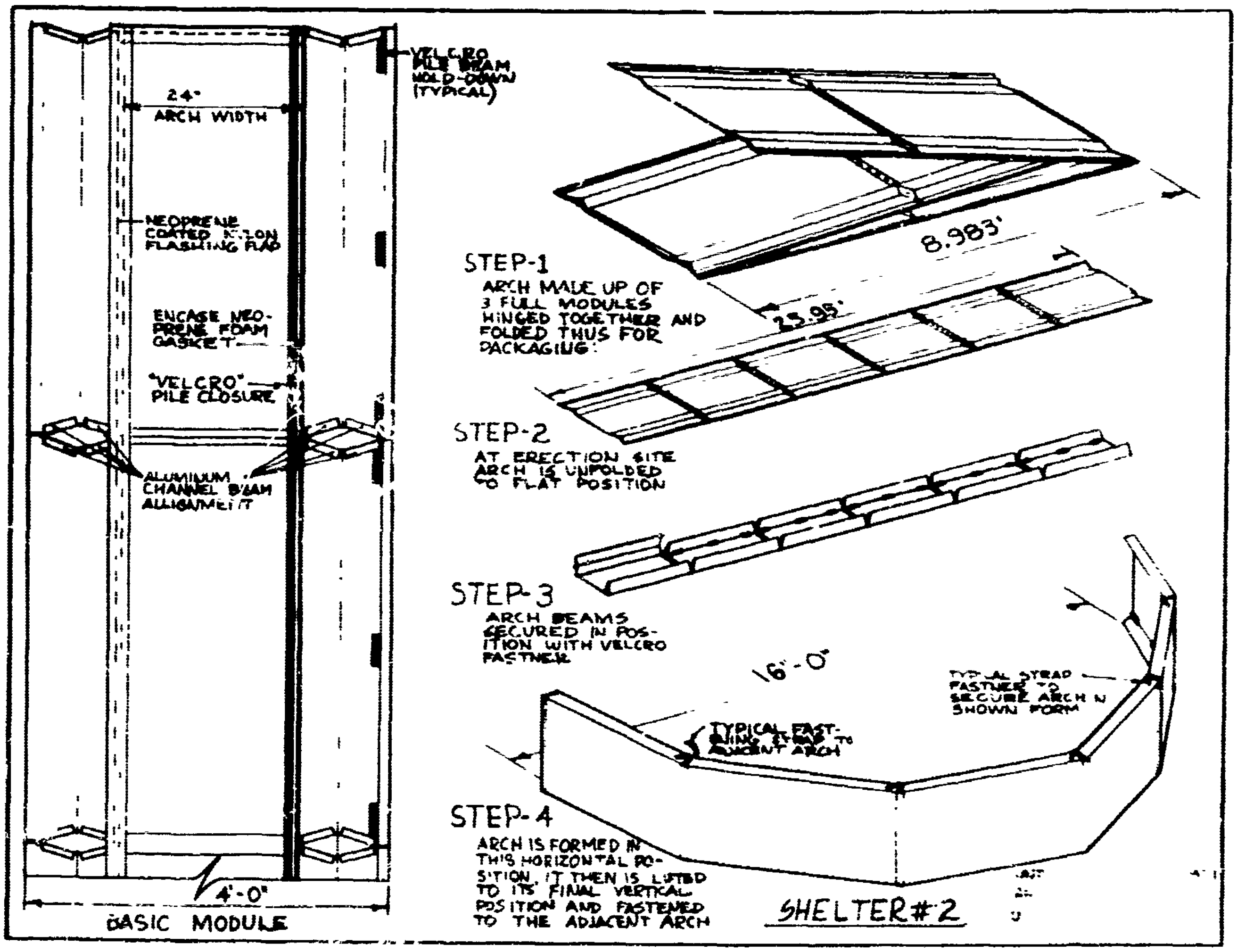


FIGURE 24. BASIC MODULE AND ARCH DRAWING ("FOLDED BEAM" CONCEPT)

Figure 25 is a rendering of a shelter utilizing the "folded beam" concept.

1.) Static Load tests

A single folded beam arch was constructed and loaded to failure. This occurred after a uniform load of 6 psf was applied. It was felt that this test was unfair as in any total structure adjacent triangular section folded beams would be securely attached to each other by continuous Velcro-lined flashing and by connecting Velcro-secured webbing straps giving greater strength and rigidity. Test results are plotted on Tables X and XI.

A second test was made on a double (4') arch. As shown on Table XII, a 10 psf loading was achieved. The arch was left loaded at the conclusion of the test and failed sometime during the night following the evening the test was made. Figure 26 shows this test arch being loaded.

2.) Adhesive and finish testing

In addition to testing the load-carrying ability of the new concept, it was decided that further investigation into adhesives and surface finishes should be made. One of the most significant features of the "folded beam" concept was the substitution of nylon Velcro fasteners for any type of mechanical connector. This change with its reliance on fabric flashing, hinging, and webbing straps, made choice of proper adhesives for various surfaces employed very critical.

These tests revealed that while many adhesives have excellent shear strength (with the paper liner often failing before the adhesive did) peel strength is critical, and the design of straps, flashings, etc. to transfer peel loads into shear loads is very important. The selection of the various adhesives listed in the specifications for Shelter #2 to follow was made as a result of these tests.

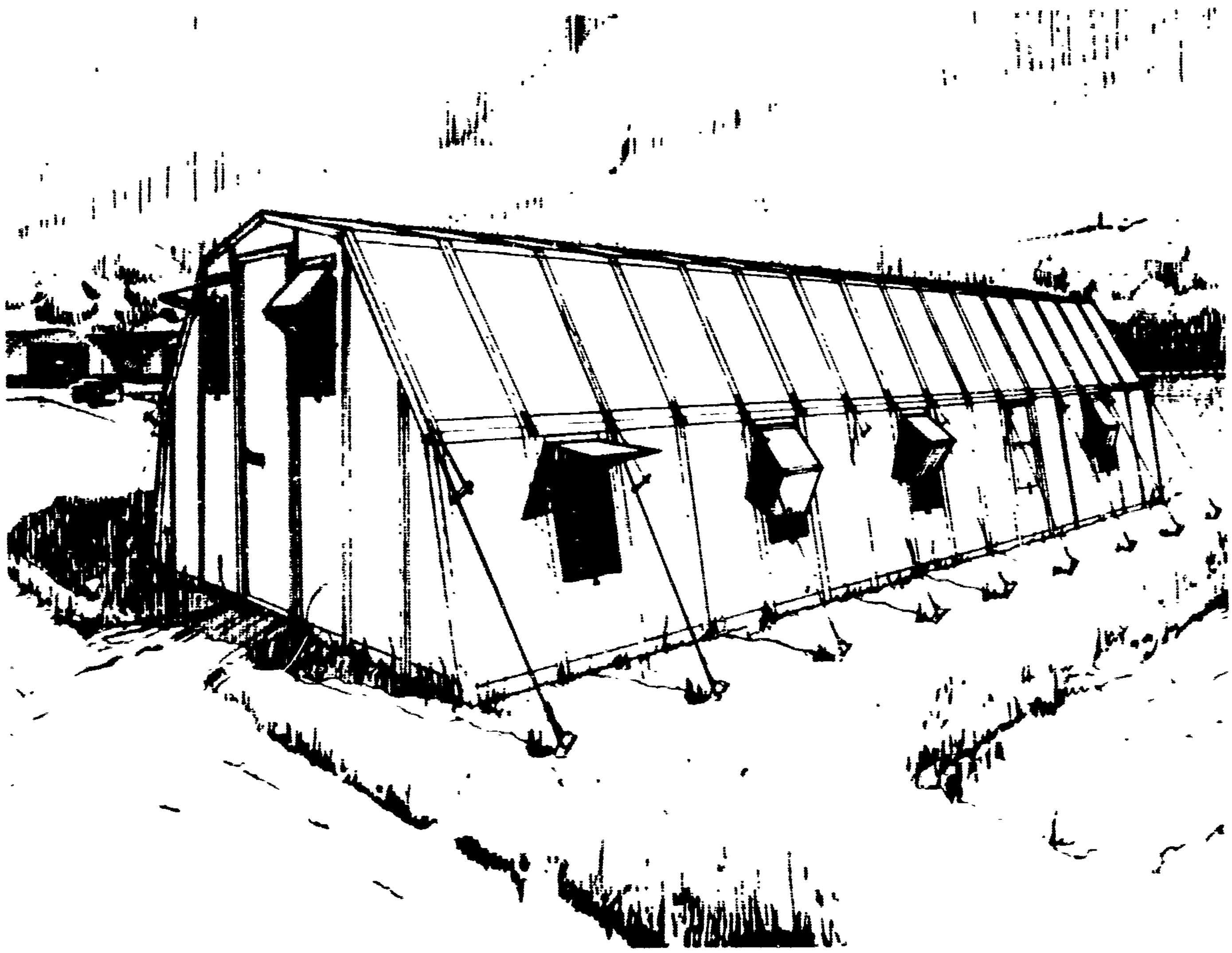


FIGURE 25. RENDERING (SHELTER USING "FOLDED BEAM" CONCEPT)

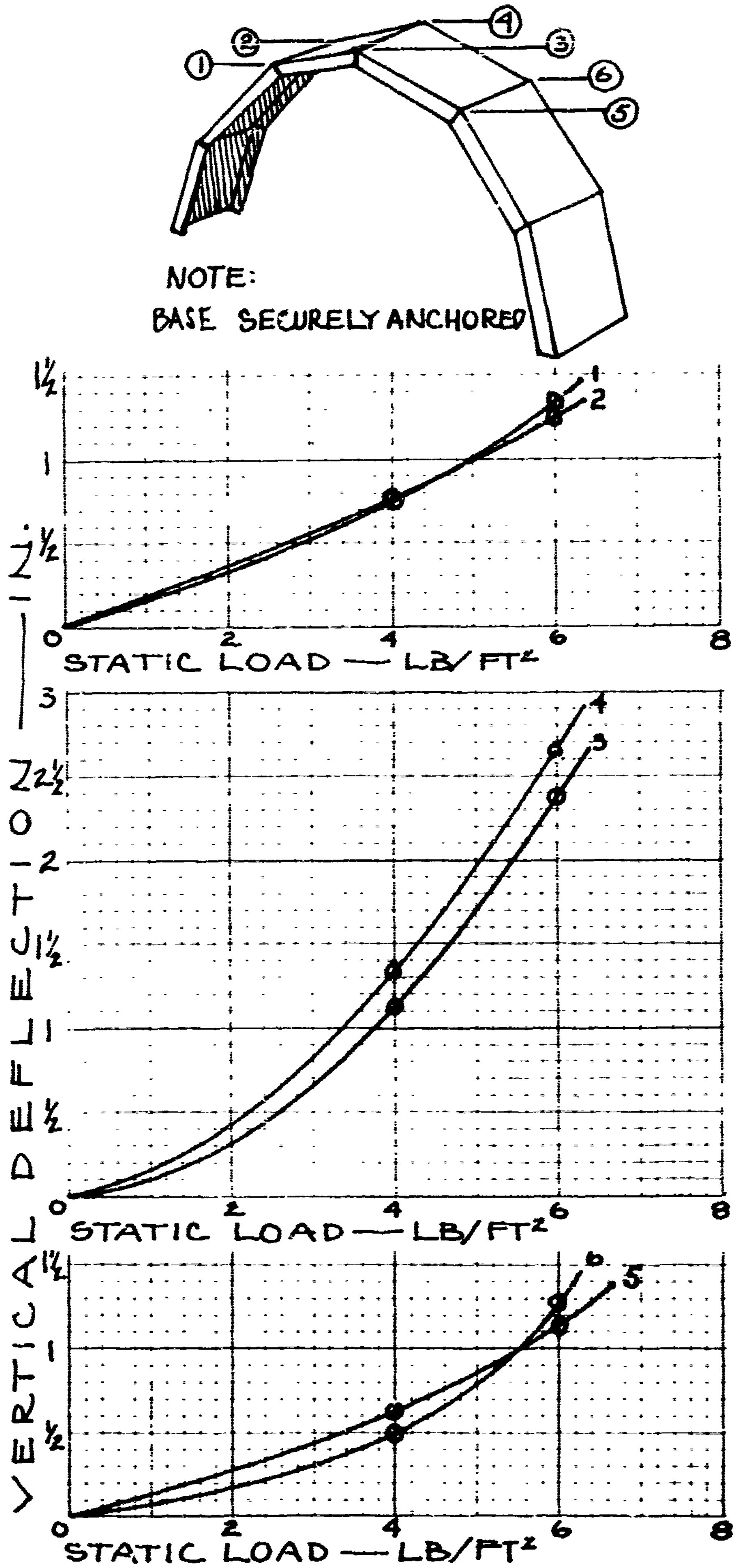
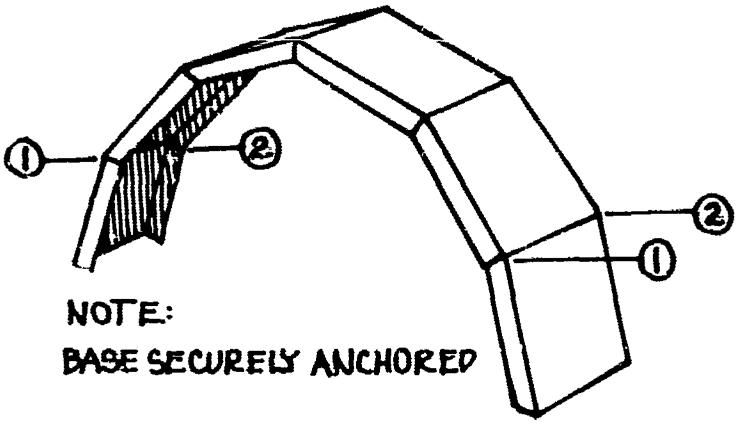


TABLE X - VERTICAL DEFLECTION TEST - FOME-COR 2' TEST ARCH ("FOLDED BEAM" CONCEPT)



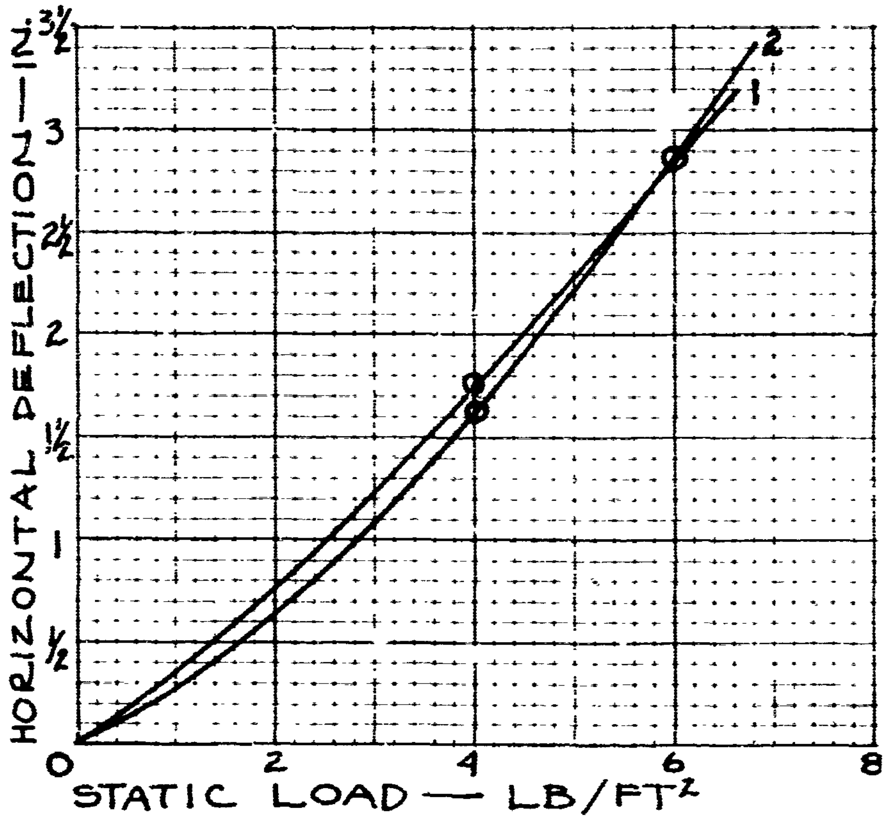


TABLE XI - HORIZONTAL DEFLECTION TEST - FOME-COR 2' TEST ARCH
("FOLDED BEAM" CONCEPT)

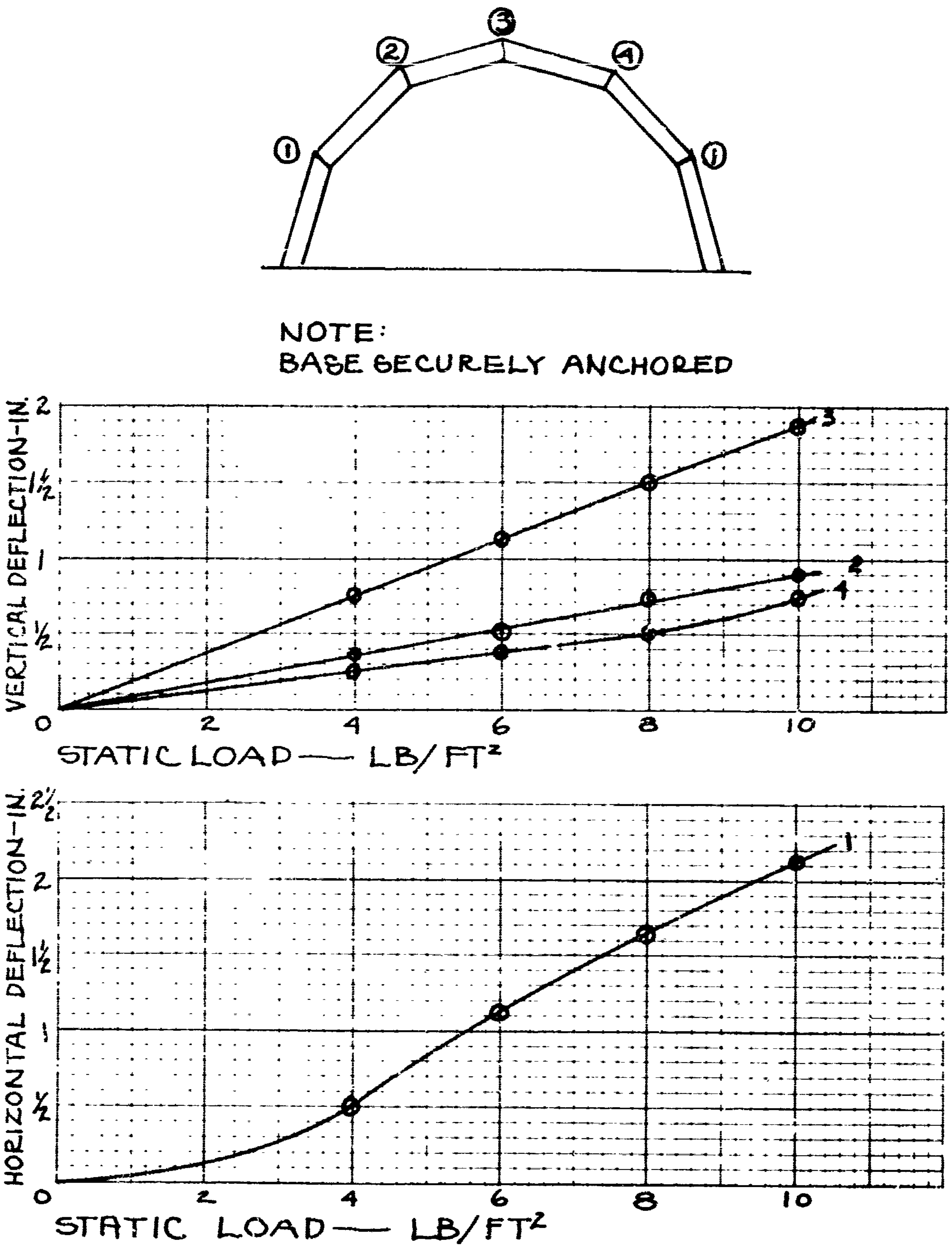


TABLE XII - VERTICAL AND HORIZONTAL DEFLECTION TESTS - FOME-COR 4' TEST ARCH ("FOLDED BEAM" CONCEPT)

While the ADM Aroflint 505 finish used on Shelter #1 had been satisfactory in most respects, its tendency to eventually crack when folded repeatedly was a cause for minor concern. It was not considered a major failure because, in the "folded beam" concept none of the folded joints was exposed to the weather in an erected structure.

An acrylic house paint made by Porter Paint Company gave early promise of overcoming this minor deficiency. Because of its more resilient composition, it showed no indications of cracking in folds. Also, it was available in a flat, non-glossy finish. Long exposure to weather, however, showed it to be inferior to the ADM epoxy type - at least for the requirements of this problem. Its ability to "breathe" (desirable in a house paint covering wood) permitted some moisture penetration leading to some warpage of the Fome-Cor and eventually to delamination of the liner.

The Perry and Derrick Co. of Cincinnati, working with the ADM Aroflint 505 formula made and tested samples that reduced the sheen of this paint and supplied it in a lighter value of Federal Standard No. 595 Lusterless 34159. Weatherometer tests by this company demonstrated in a 200-hour test the weather-resistance not only of the modified Aroflint 505 finish but the following adhesives: Fuller #915 (used for attaching webbing to the painted Fome-Cor) and 3-M Fast bond #10 (used for attaching neoprene-coated nylon flashing to the painted Fome-Cor).

To assure fire-resistant qualities of the shelter material several tests were made. Fifteen-second exposures to a blow torch at four-inches distance and two-minute exposures at twelve inches were tried. Although Vamasco Fire Retardant Paint gave the best results, the ADM Aroflint #505 was a close runnerup and had many other superior qualities in solving the overall finish problem.

H. CONSTRUCTION OF SMALL SHELTER #2

In accordance with the amendment to the contract a 16' wide x 32' long shelter was constructed. Originally intended to be merely a modification of the first shelter, the development of the "folded beam" concept with its obvious advantages over the "bow-tie" concept dictated that this concept be employed in Shelter #2. Approval of this decision was given by the Project Engineer.

As constructed and erected at the university, Shelter #2 had the following features and materials:

Structure: "folded beam" arches of 1/4" Fome-Cor with Velcro attachment to each other and to grade beam, Neoprene-coated nylon arch and grade beam flashing, Tedlar panel hinges.

End treatment: similar to Shelter #1, but with folded Fome-Cor door heads and jambs (no wood) and heavy fabric door hinges.

Grade beam: fabricated alum[illegible] (See Figure 27).

Exterior and interior protective finish: ADM Aroflint 505 - Exterior 2 coats olive drab, Interior 2 coats off white.

Adhesives (in appropriate applications): 3M Fast bond 30, Fuller #915, Velcro #45, Elmer's casein.

Insulation (optional): 1" thick panels of gold Bond Zero-Cel polyurethane foam board attached with Velcro.

Windows: rectangular Tedlar hinged cutouts in Fome-Cor, screened inside, bi-fold grometted shutters riding on venetian blind operating cords.

Skylights: fixed 1/4" thick clear acrylic sheets.

Construction was accomplished during late February and early March, 1965. The completed shelter was pre-assembled at the college, then disassembled and packaged for shipment to its test site.

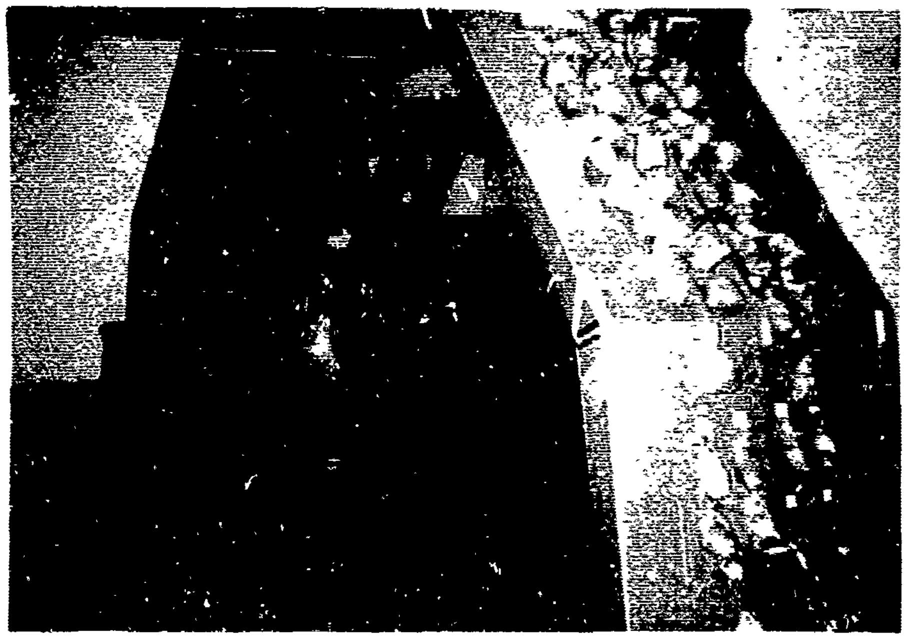


FIGURE 26. STATIC TESTING OF FULL SIZE ARCH ("FOLDED BEAM" CONCEPT)

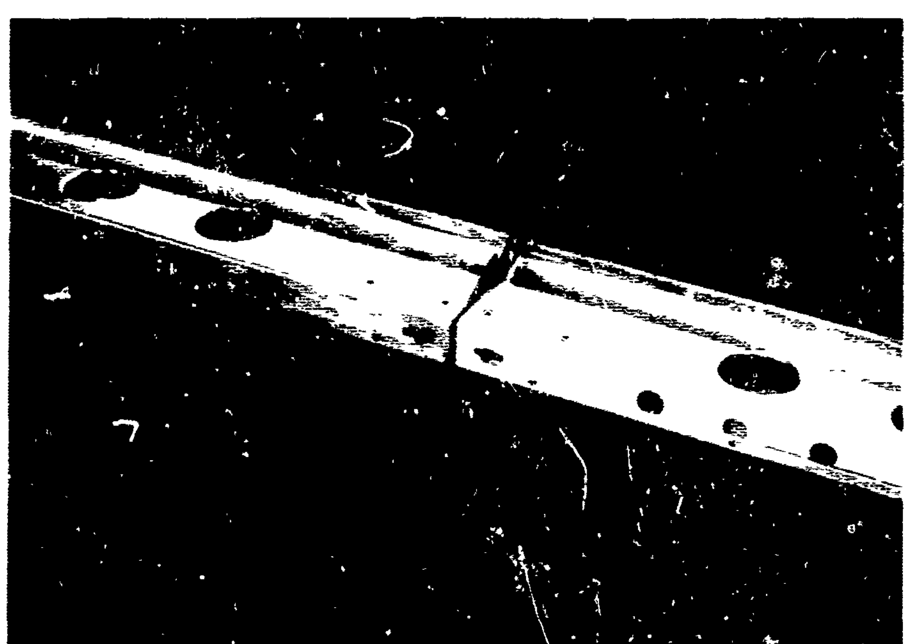


FIGURE 27. ALUMINUM GRADE BEAM, SHELTER #2 (TYPICAL SECTIONS AND CONNECTOR)

Views illustrating the production sequence of the basic panels (scoring, cutting and folding) can be seen in Figures 28 and 29.

I. FIELD TESTING OF SMALL SHELTER #2

On 18 March, 1965 Small Shelter #2 was shipped by air to Langley AFB, Virginia for erection and testing.

The shelter was packaged for shipment in six packages, each approximately 4'4" x 9'0" x 7" thick. Total weight of the shelter (including the aluminum grade beams but not including stakes, tarpaulin or optional insulation) was 630 lbs. Insulation was packaged separately. The packaged shelter is shown at the test site in Figure 30.

On 22 March a five-man team from the University of Cincinnati arrived at Langley AFB and, after reporting to Civil Engineering Office, Headquarters TAC, erected the shelter at a selected site near the base commissary.

Erection time for Shelter #2 was two hours and fifty-five minutes for the five-man crew (approximately fifteen man hours). Erection time would have been less except for (1) approximately one-half hour having to be spent in alignment and installation of the large door at the end of the shelter due partly to the site (and hence the end grade beam) not being level, and (2) the amount of time spent explaining and demonstrating steps of erection for the visiting Air Force personnel and Air Force photographers.

Erection was accomplished in gusty weather so care was exercised in unfolding and carrying the lightweight arches.

Figures 30 through 38 are photographs taken during the erection at Langley AFB.

Heavy winds during the first twenty-four hours caused two things to happen: (1) the left hand panels of both ends of the shelter were blown loose, and (2) the entire shelter shifted as a unit

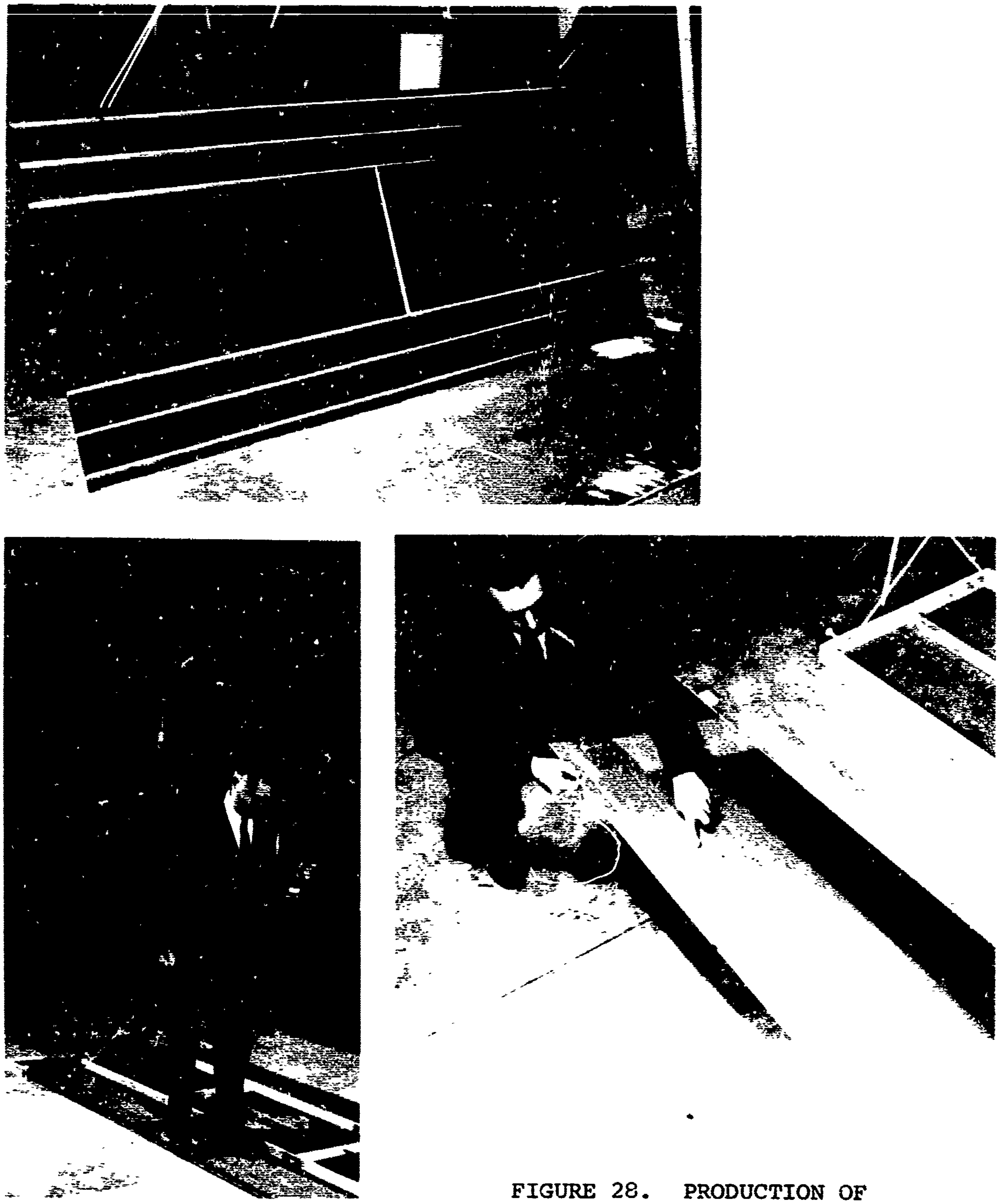


FIGURE 28. PRODUCTION OF "FOLDED BEAM" MODULES (SCORING WITH TEMPLATE)

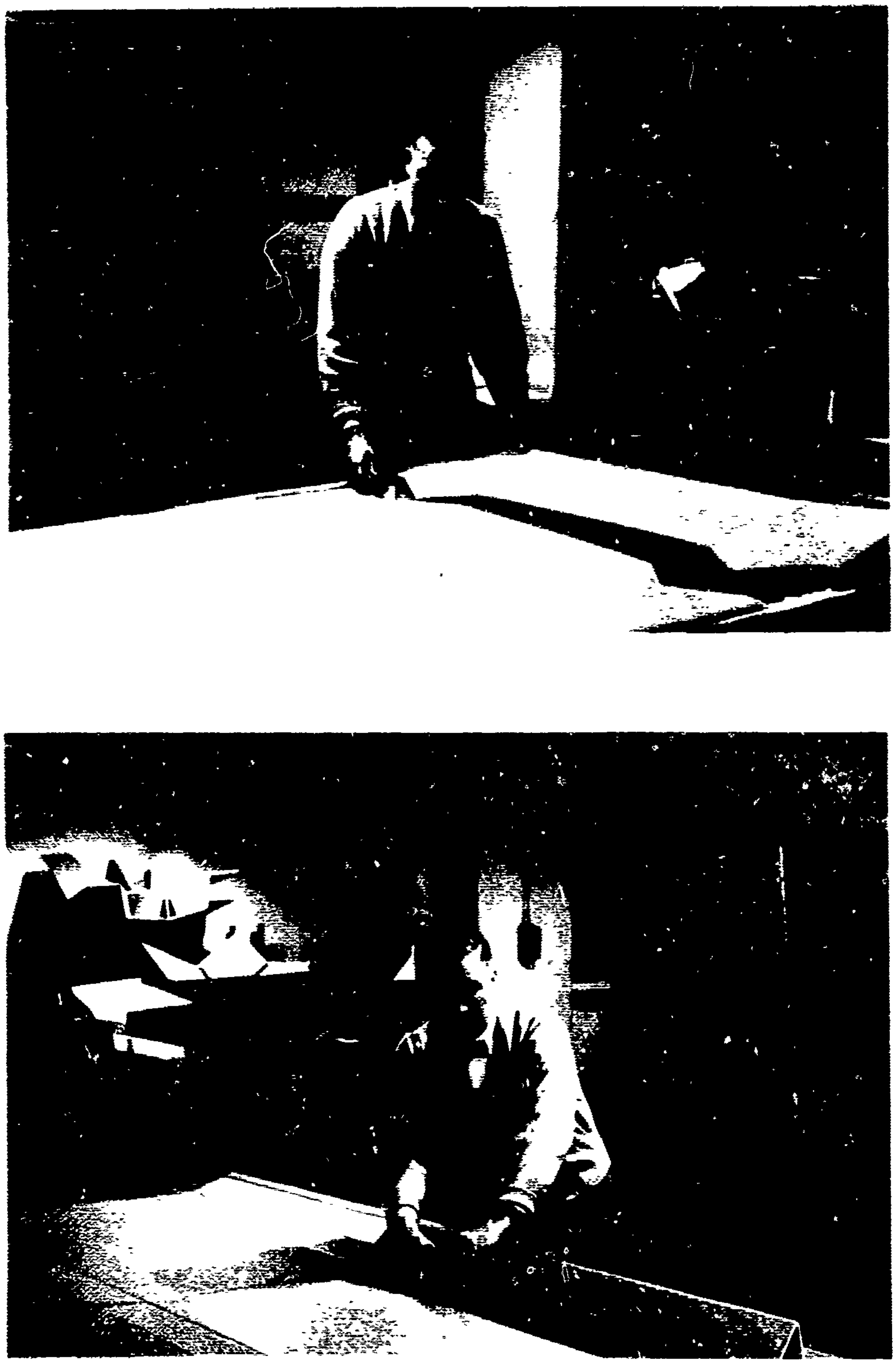


FIGURE 29. PRODUCTION OF "FOLDED BEAM" MODULES (CUTTING AND FOLDING)

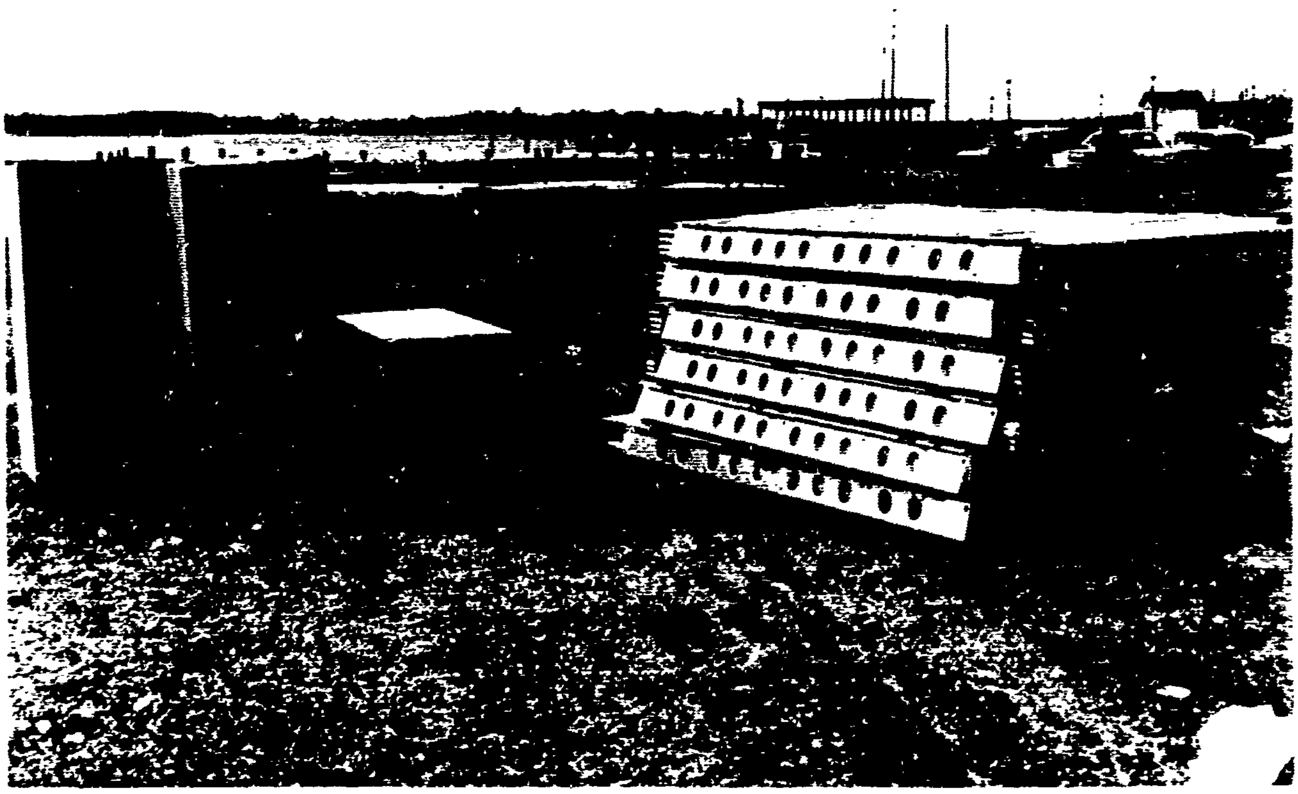


FIGURE 30. SHELTER #2 FIELD TEST, LANGLEY AFB BASIC PACKAGE
(INSULATION KIT, LEFT; SHELTER COMPONENTS, RIGHT)

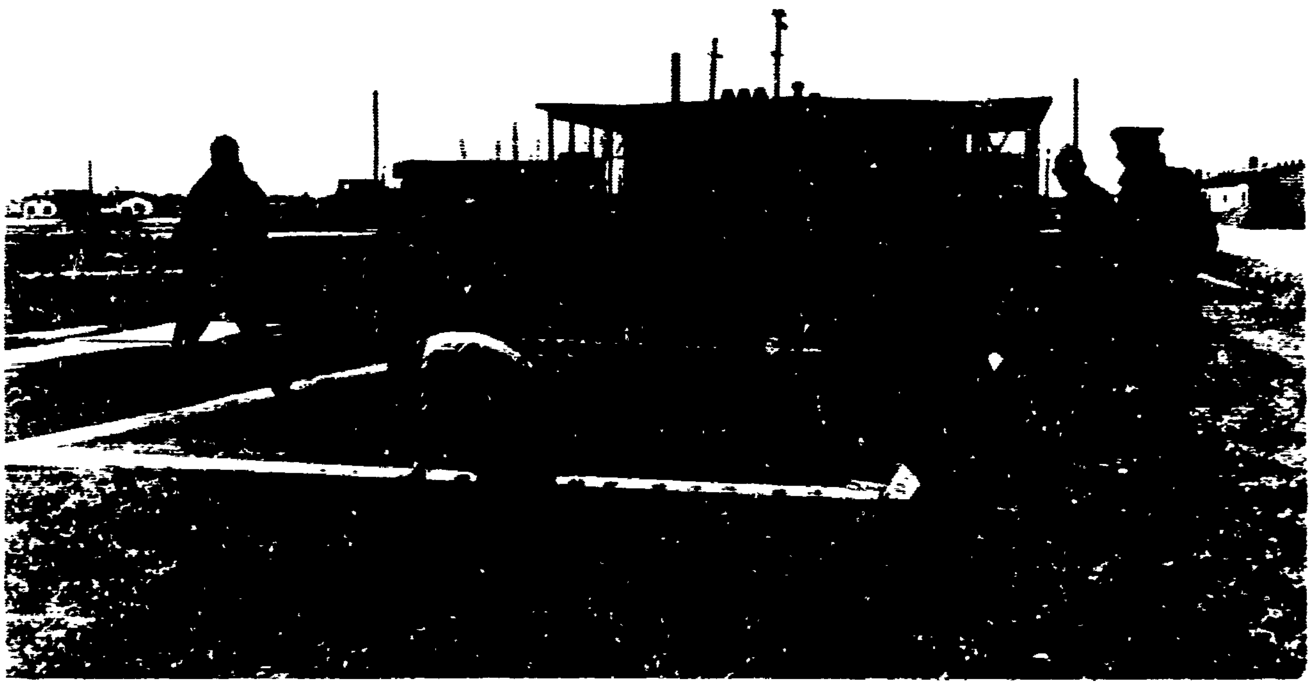


FIGURE 31. SHELTER #2 FIELD TEST, LANGLEY AFB
(INSTALLATION OF ALUMINUM GRADE BEAM)

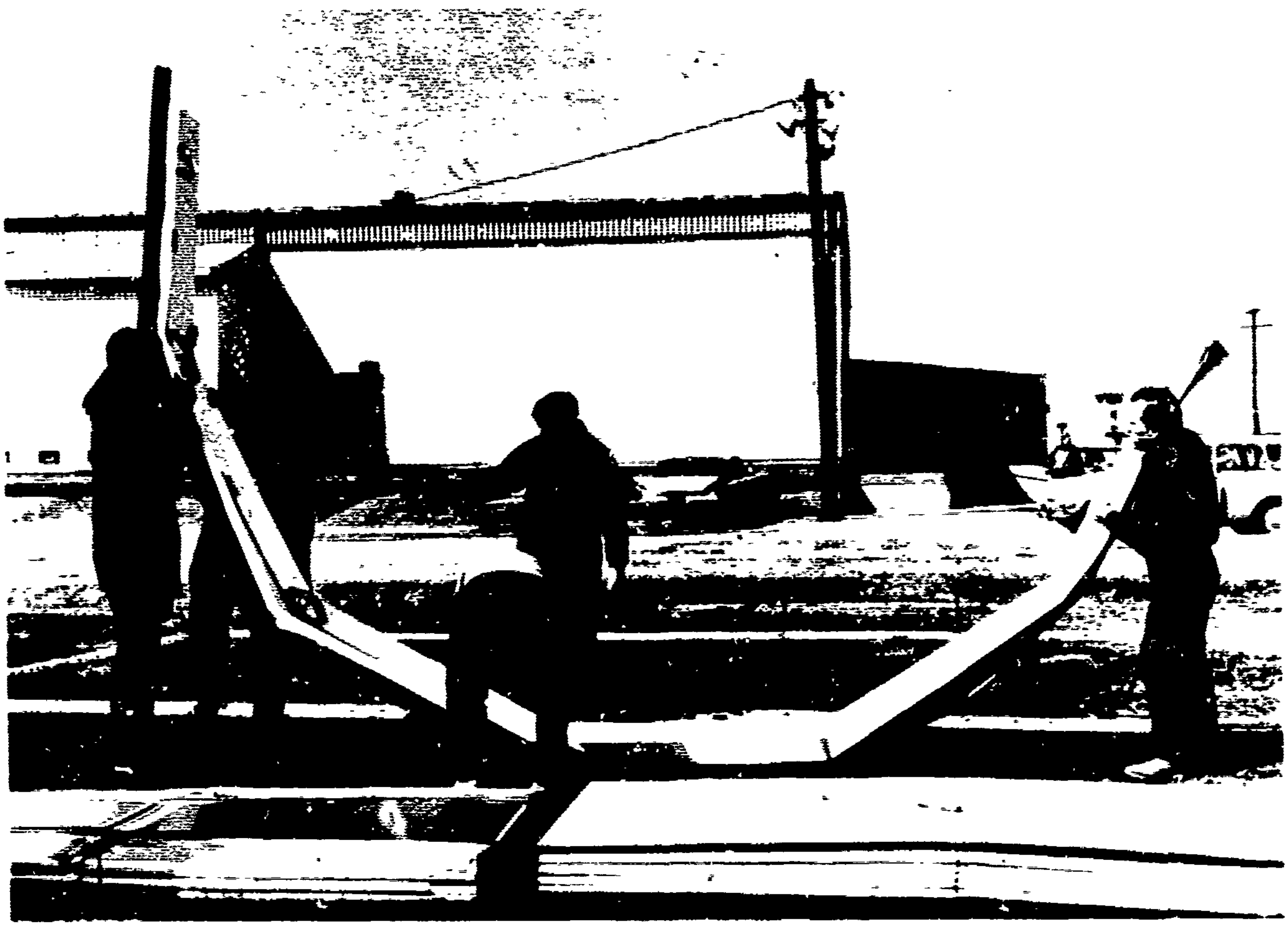


FIGURE 32. SHELTER #2 FIELD TEST, LANGLEY AFB
(FOLDING OF FIRST ARCH)

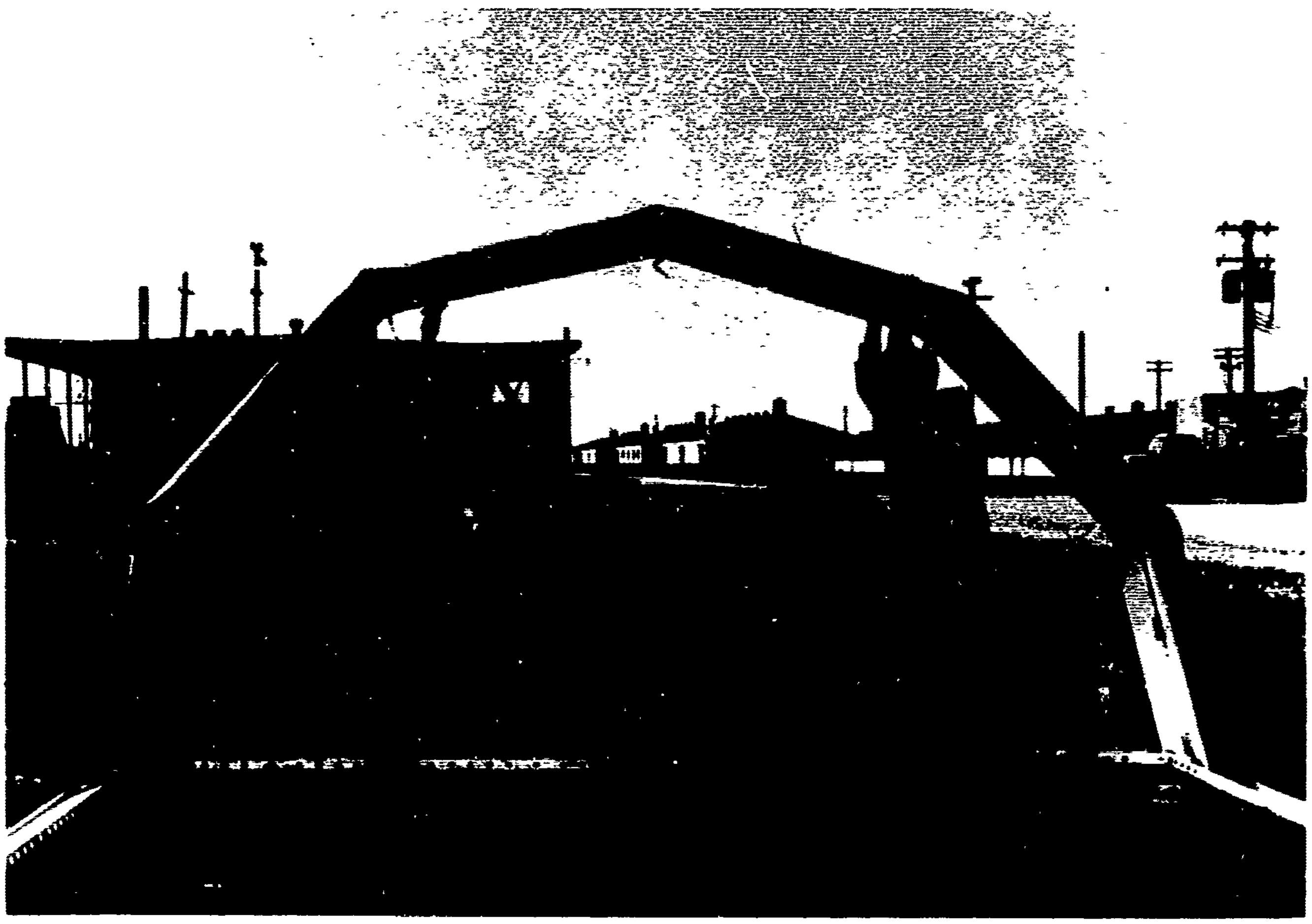


FIGURE 33. SHELTER #2 FIELD TEST, LANGLEY AFB
(INSTALLATION OF FIRST ARCH ON GRADE BEAM)

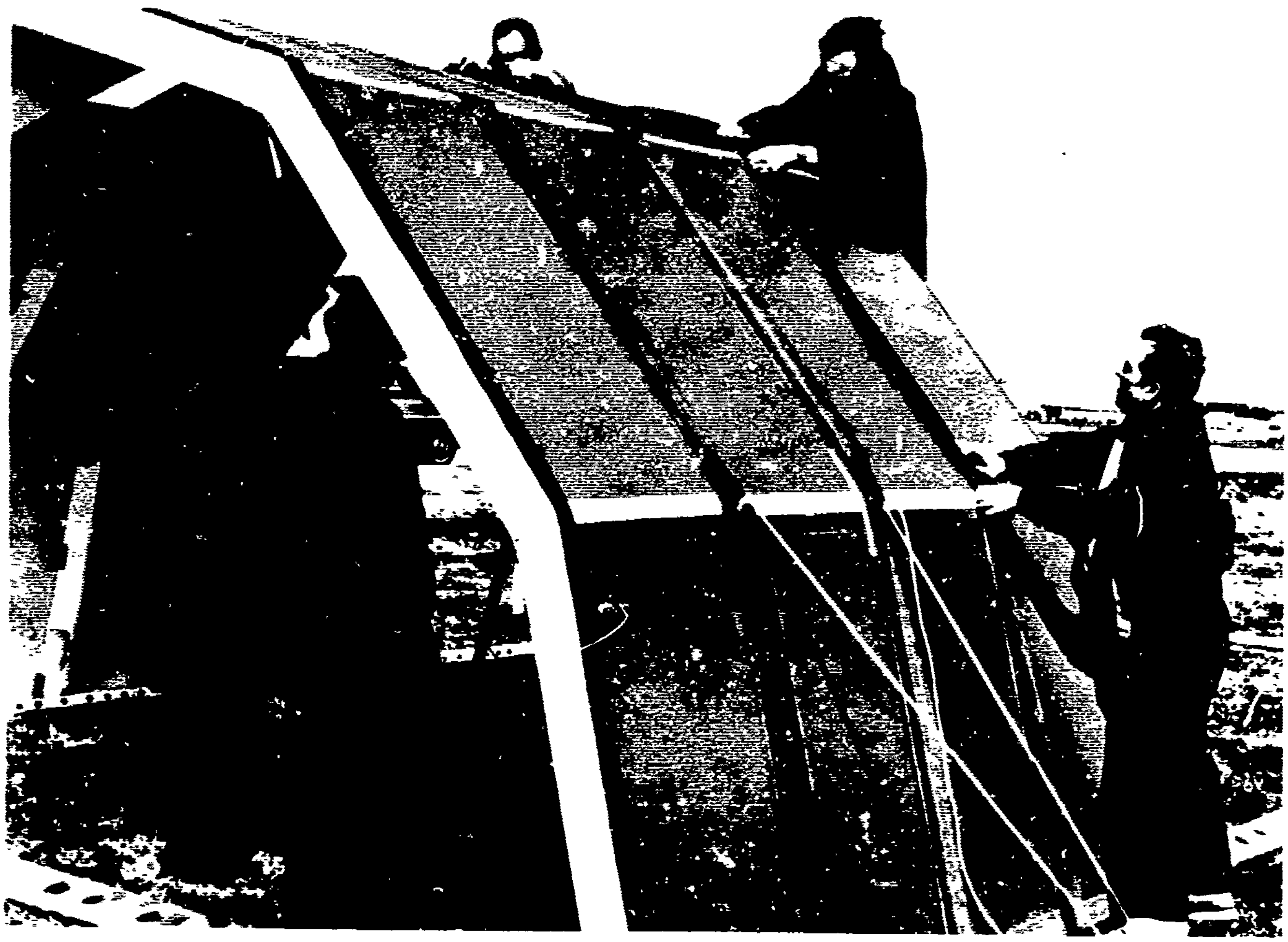


FIGURE 34. SHELTER #2 FIELD TEST, LANGLEY AFB
(JOINING AND FLASHING ADJACENT ARCHES)

FIGURE 35. SHELTER #2 FIELD TEST, LANGLEY AFB
(INSTALLATICN OF END COMPONENTS)

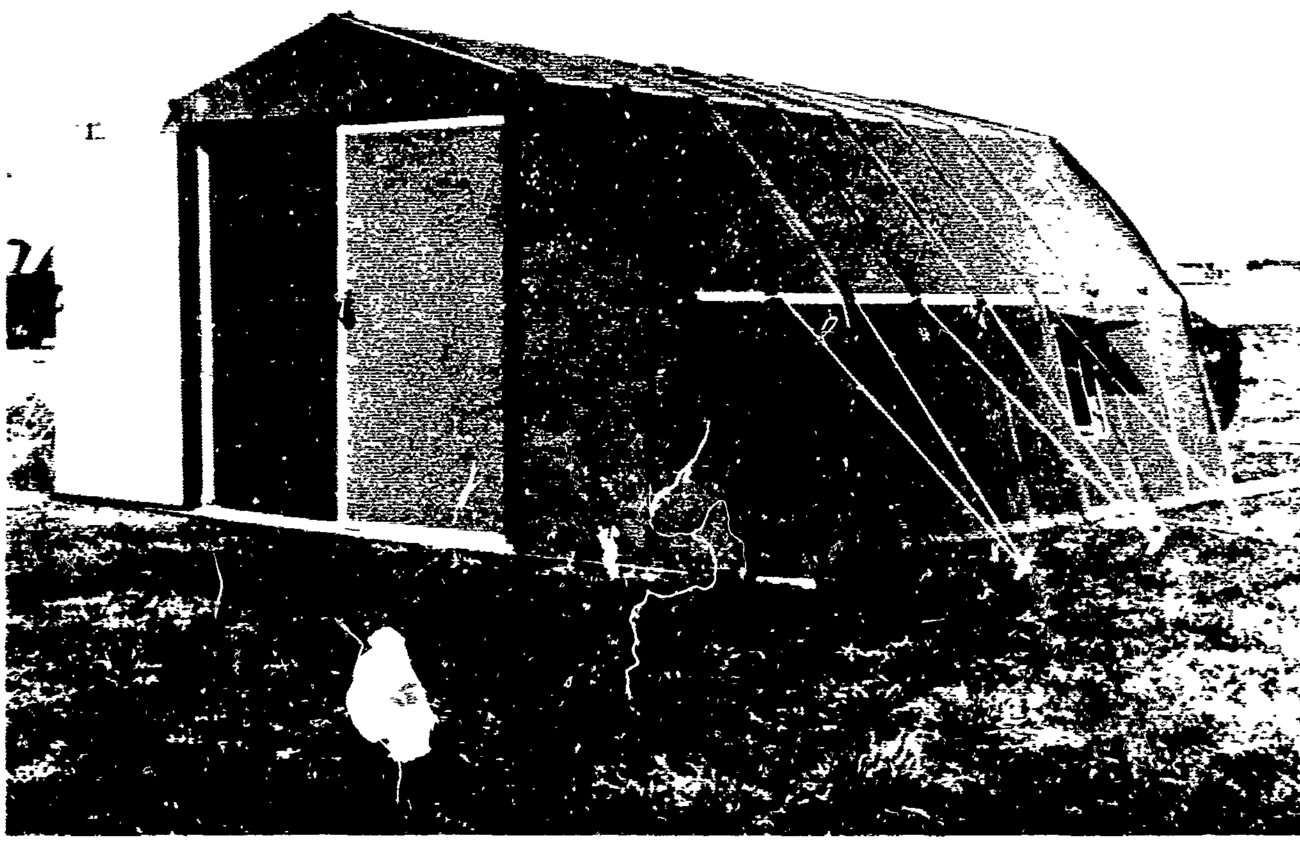


FIGURE 36. SHELTER #2 FIELD TEST, LANGLEY AFB
(ERECTION FIFTY PERCENT COMPLETE)

FIGURE 37. SHELTER #2 FIELD TEST, LANGLEY AFB
(INTERIOR VIEW SHOWING INSTALLATION OF END COMPONENTS)

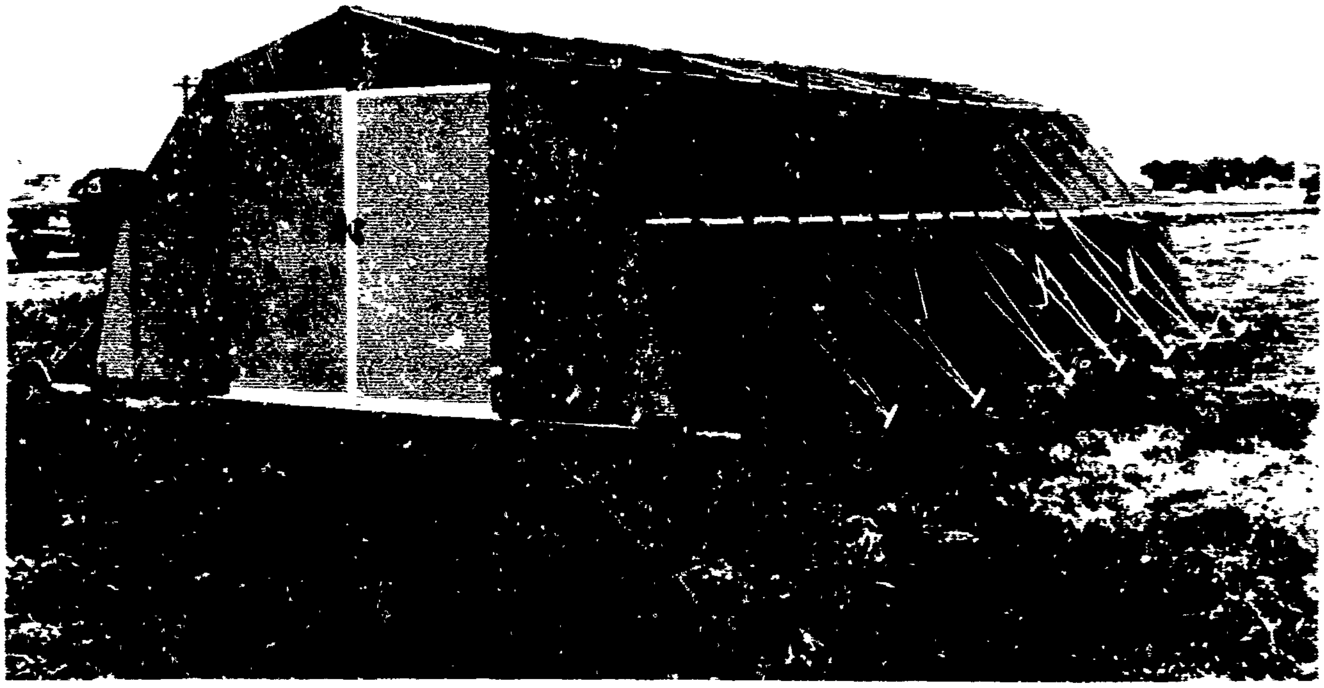


FIGURE 38. SHELTER #2 FIELD TEST, LANGLEY AFB
(COMPLETED SHELTER SHOWING LARGE DOOR END)

approximately three inches. The first occurrence was a by-product of the difficulty in aligning the doors during erection (the ends and doors have subsequently been redesigned). The shifting occurred as a result of inadequate staking in the soft earth that apparently had a gravel or paved area approximately six inches below grade. Corrective action was taken and no further difficulty was encountered.

One university team member remained at Langley until 26 March, the other members having returned on 23 March. He reported no further shifting, leakage, or problems of any kind in spite of continued high winds and continuing showers.

During this week the shelter was visited by the Deputy of Engineering, the Command Surgeon and other Civil Engineering personnel, Headquarters TAC. Comments varied from enthusiastic reaction to skepticism on some aspects. Some concern was expressed that the shelter might not be sufficiently "G.I. proof" in repeated handling and use. Those who viewed it as competition for a tent thought it was expensive. Those who saw it as the gap-filler between the tent and heavier, more conventional structures expressed optimism.

On 21 April, the university team member returned to Langley and, with the help of two civilian employes of the base, dismantled the shelter in two hours and five minutes (6 1/4 man hours).

The one-month test period had showed no physical deterioration of any part of the structure. In spite of heavy rains and strong winds, periodic checks by TAC engineering personnel revealed no leakage or movement of the shelter. A slight oxidation of the neoprene-coated nylon flashing that gave a lighter color to this material was the only sign of visible appearance change.

Following the field test, the team re-evaluated certain aspects of the shelter design and decided the end walls should be reconstructed with additional reinforcing struts and more positive anchorage to the gable and to the grade beam. This redesign was started and materials ordered.

J. SUBSEQUENT TESTING AND MODIFICATION OF SMALL SHELTER #2

1.) Minneapolis, Minnesota

The next erection of Shelter #2 was at Minnetonka Beach, Minnesota in connection with the Second Aerospace Expandable Shelter Conference, 26 & 27 May, 1965. A paper covering work performed to date under this contract was presented at the conference, and the shelter was erected and demonstrated as an exhibit.

Delay in returning the shelter from Langley AFB until immediately prior to the Minneapolis conference made it impossible to install modified end walls so the structure was in the same form as it was at Langley.

Erection here was performed by a four-man university crew in three and one half hours (fourteen man hours) in spite of several interruptions by rain, photographers, reporters and other interested parties.

One observer at the erection demonstration made spot checks on erection time for some of the parts. His report was that the four-man team required only three minutes to unfold an arch unit, to form and fasten it into its arch shape, and to set it on the grade beams and complete the fastenings and flashings to the adjoining arches already in place.

The temperature during most of the test ranged from 35 to 55 degrees. The wind during much of the test was steady and about 30 knots. Several showers occurred. The shelter was disassembled on 27 May during the 30-knot wind and 35-degree temperature. The lightweight panels required careful handling in the wind, but the operation progressed satisfactorily until only four arches and the large-door end remained. At this point several hard gusts of wind occurred in quick succession. The end wall gave indication of impending failure. It was immediately removed, which then subjected the remaining arches to the possibility of blowing down or blowing away.

Two additional men were quickly recruited for about five minutes to help hold the remaining arches until the team could disassemble the arches and lay them on the ground in a folded position to prevent their blowing away. This operation was safely accomplished and the parts were repackaged for shipping back to Wright-Patterson AFB. The operation of disassembly, repackaging, stacking, and covering took four men about two and one half hours (ten man hours).

Figure 39 shows shelter #2 in place on the shore of Lake Minnetonka.

2.) Wright-Patterson AFB, Ohio

Two other erections were made at two different locations at Wright-Patterson AFB at the request of the project engineer. The erections were for demonstration purposes, and the structure stood erected about three weeks in late June and July. No unusual weather was encountered during this period. One minor failure, attributed to the intense heat from the sun, was a minor creeping of the Tedlar hinges between modules of the arches. It was decided that substitution of a scored neoprene-coated nylon hinge here would be an improvement.

In the handling of the packaged shelter in its travels from Ohio to Virginia to Minnesota and back to Ohio some minor damage had occurred. A fork-lift blade tore one aluminum grade beam badly so that while still serviceable, it has been replaced with a spare. At the same time one module was badly ripped (apparently by the fork-lift blade) and had to be patched. Other minor rips in the edge of the module (about ten in the entire shelter with an average length of one inch) had to be patched with Tedlar tape.

It should be noted that erections at Wright-Patterson AFB were erections number four and number five, and that the number of erections called for in the original program was five.

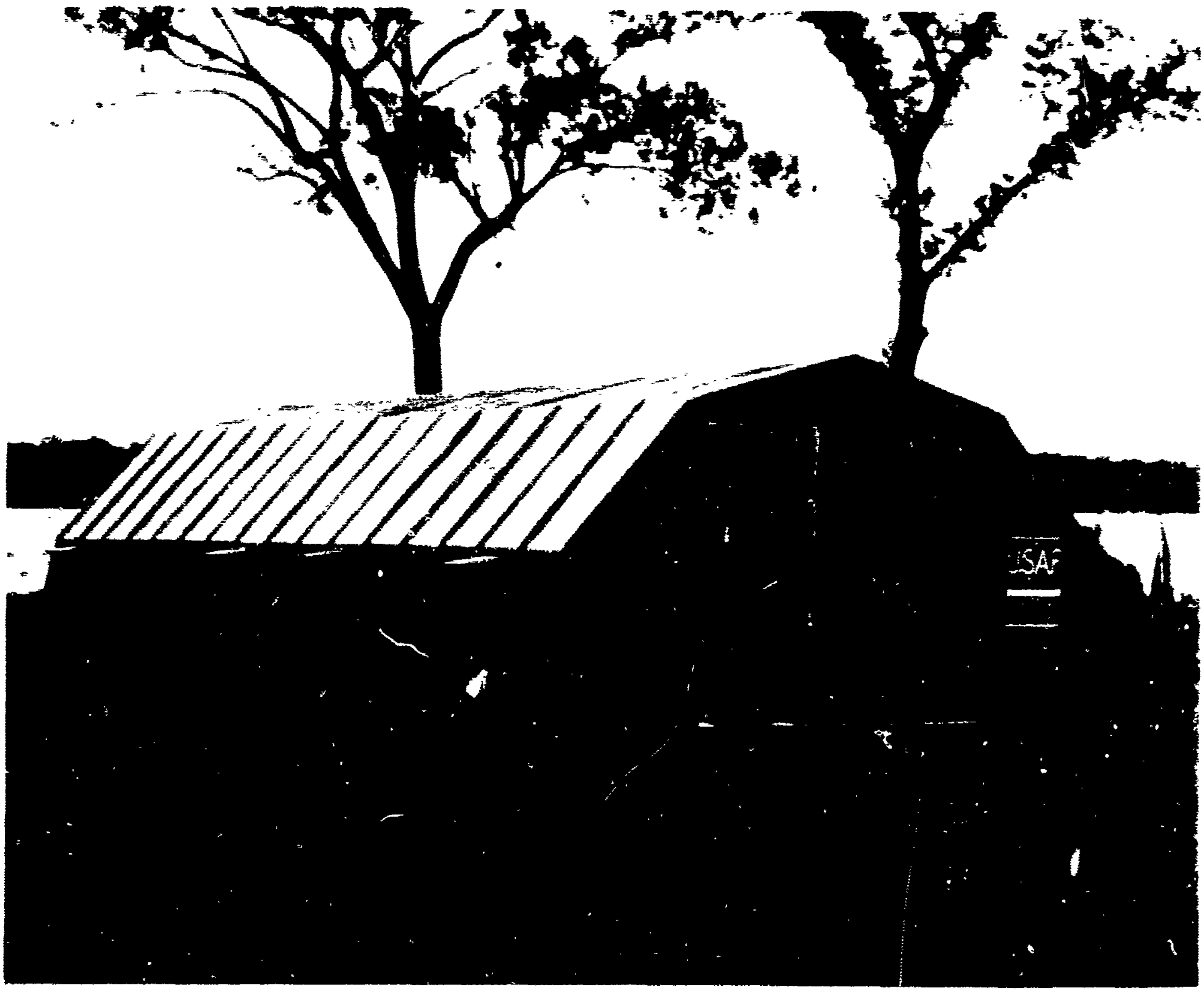


FIGURE 39. SHELTER #2 SECOND AEROSPACE EXPANDABLE STRUCTURES CONFERENCE, MINNETONKA BEACH, MINNESOTA. (ERECTED SHELTER SHOWING SMALL DOOR END)

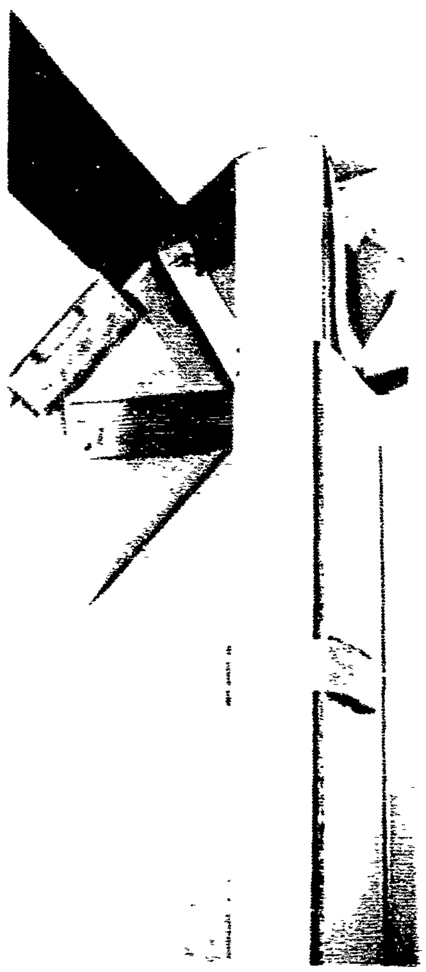
3.) New end design

In accordance with plans established after the Langley Field test period, new ends were designed and constructed during August, 1965. With the approval of the project engineer the design of both ends was made identical, each end having a 3' x 7' door.

Under an addendum to the contract for the large hangar prototype (see Section I - INTRODUCTION) further tests for Small Shelter #2 are being programmed. The shelter has been refurbished in preparation for the first of these tests (at U.S. Army Tropical Testing Center, Panama Canal Zone, September 1965) by (1) substitution of rebuilt shelter ends for original ones, (2) reinforcing Tedlar module hinges with neoprene-coated nylon, and (3) minor improvements and maintenance on window units.

The new end units are illustrated in Figures 40 through 42. Main features include a new lightweight aluminum door frame design and four rectangular section folded columns per end that are attached to the roof panels of the end arch and the grade beam.

In repackaging Small Shelter #2 for the Panama test an unanticipated bonus advantage was realized in that the new end assemblies require less packing space and can both be packaged in one rather than two packages. This reduces the total packages for the shelter from six to five, a reduction in cubage of sixteen and two thirds percent.



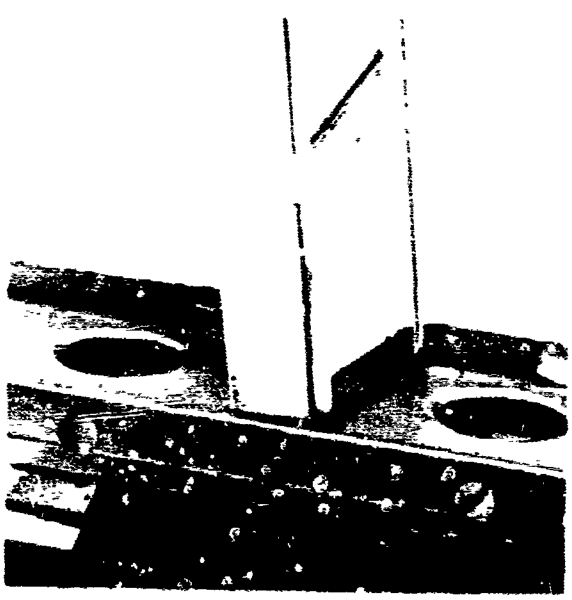


FIGURE 40. SHELTER #2 - NEW END. FOLDED COLUMN DETAILS (TOP END CONFIGURATION, BOTTOM END CONFIGURATION, INTERIOR PLACEMENT OF COLUMNS)

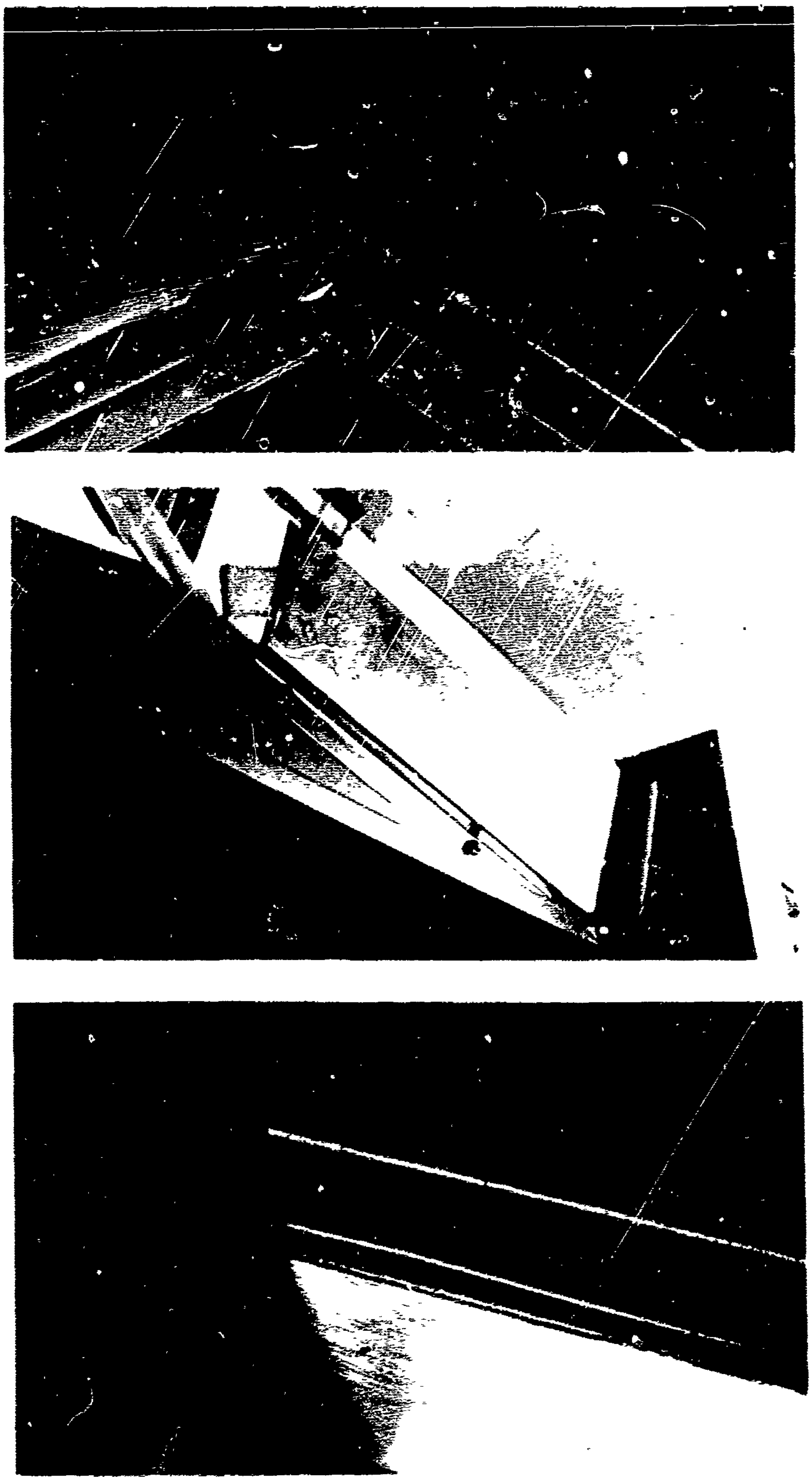


FIGURE 41. SHELTER #2 - NEW END, DOOR DETAILS (HEAD-JAMB JOINT, HEAD ATTACHMENT TO FOLDED BEAM, THRESHOLD-JAMB JOINT)

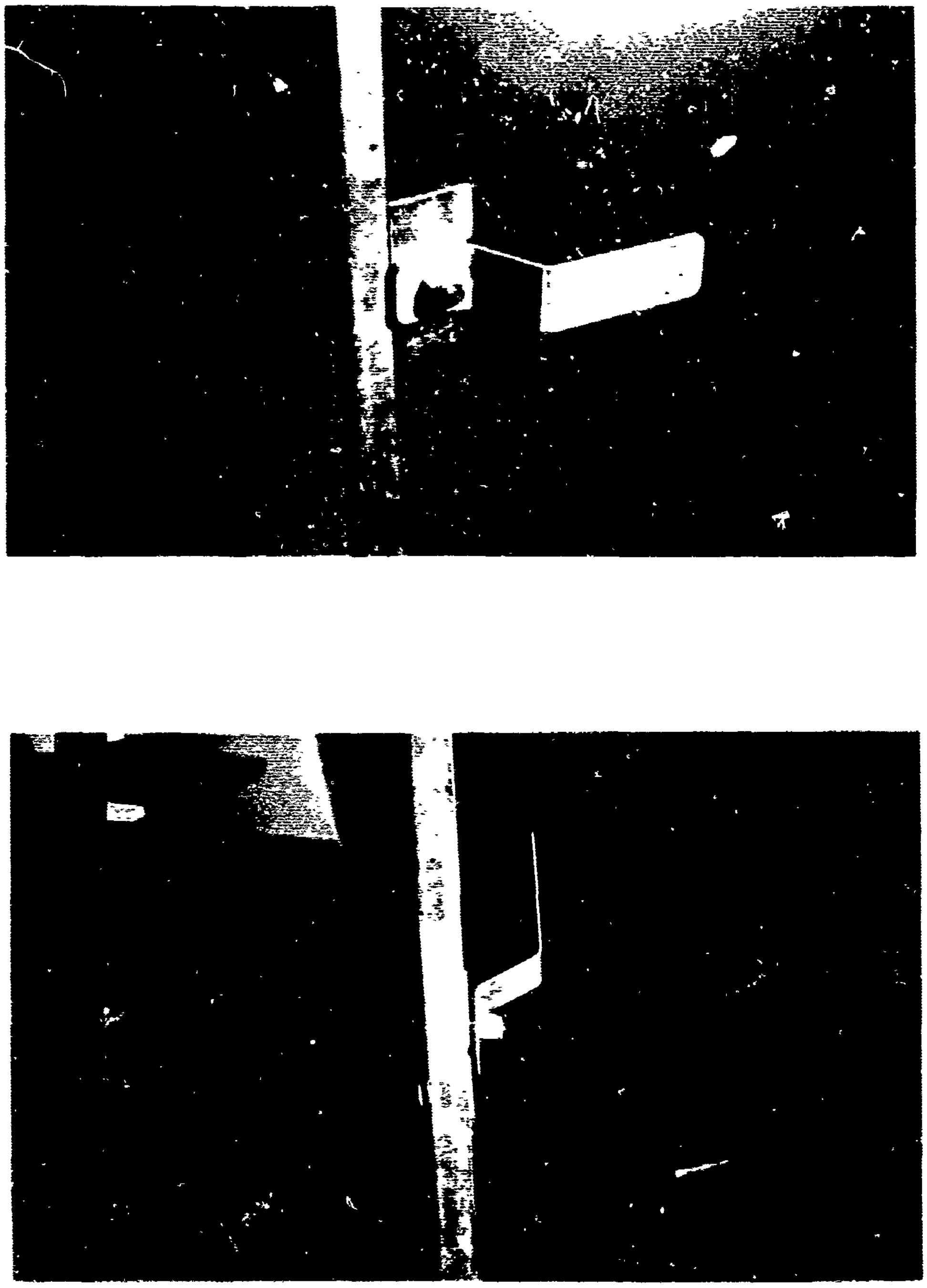


FIGURE 42. SHELTER #2 - NEW END, LATCH DETAILS (OUTSIDE VIEW, EDGE VIEW)

K. SMALL DISPOSABLE SHELTERS

Though not part of the required work under this contract, at the request of the project engineer, several concepts for inexpensive small expandable disposable shelters were evolved by this contractor. They are pictured in sketch form in Figure 43.

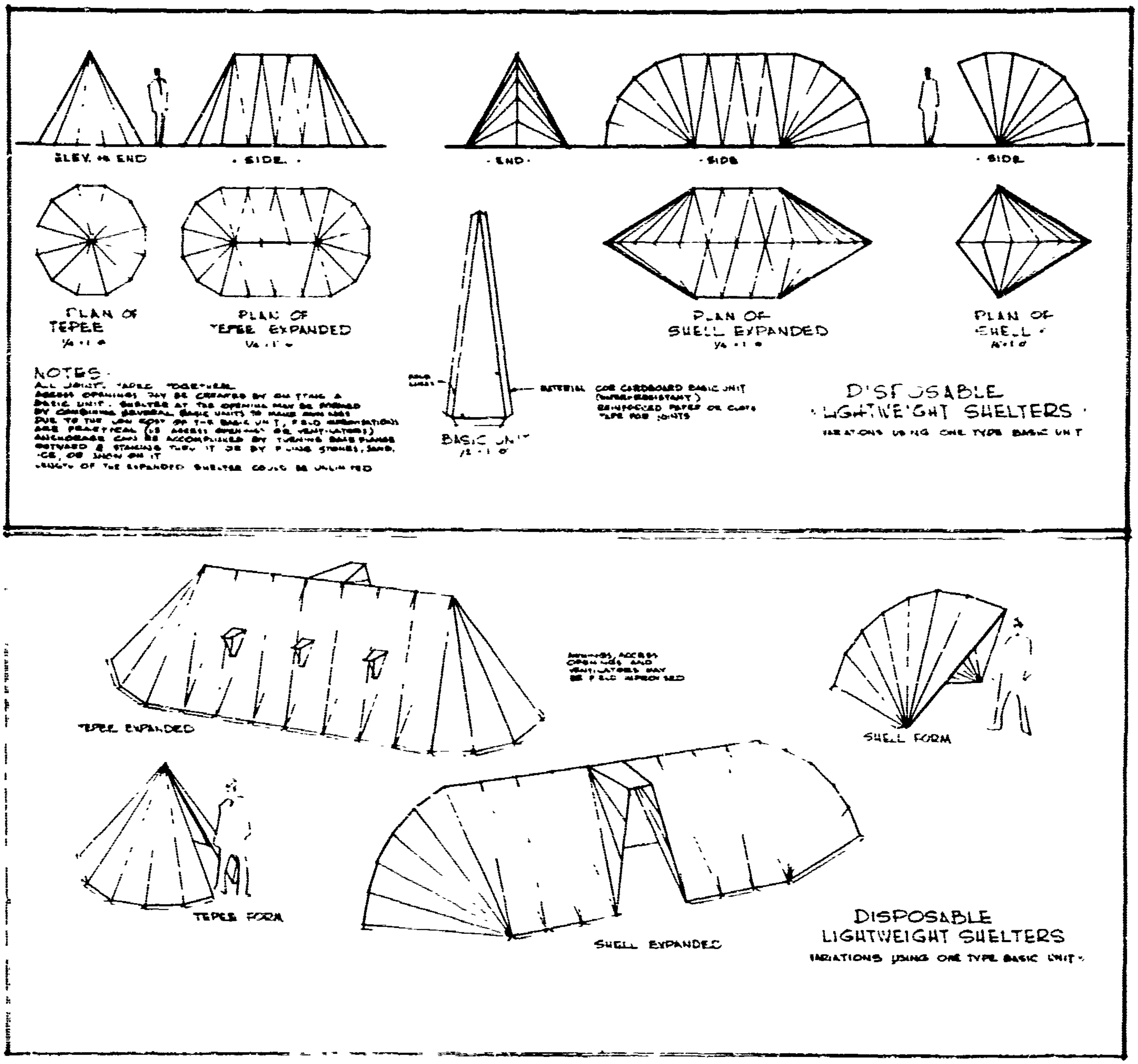


FIGURE 43. DISPOSABLE LIGHTWEIGHT SHELTER CONCEPTS

IV. LARGE SHELTER CONCEPTS

This section of the report covers the hangar design concepts in a chronological order of studies as they occurred, without an attempt to place them in an order or practicality, economic or technical feasibility, aesthetic or personal preference.

A. BACKGROUND

The original contract required new and unique design concepts for a shelter to house a Cessna type L-28 (U-10) aircraft.

As noted in the introductory statements of this report, investigations, interviews, and preliminary fact finding studies made it apparent that the needs for a hangar with immediate use possibilities should take precedence over unique and new design concepts.

The practical and immediate usage requirements became more definite as to size, load conditions, and function. More conventional materials and construction methods were to be investigated, althouth the original guiding principles were still considered valid.

The hangar was to be increased in size from a shelter for a L-28 to a nose dock for a F4B fighter. The applied live load was increased to 10 psf. Investigations were to be primarily in the area of panelized structures in preference to tent type structures. Shelters should be capable of 1-1/2 to 2 years field usage.

To follow the revised direction of study meant that materials, weight, package size, handling and shipping methods, erection time and techniques, and costs would probably be increased.

After some further study and evaluation, the direction of the requirements was set for a hangar to completely house a F-4C fighter plane. The dimensions were set at 50' wide, 80' long, and 25' high at the center to accommodate the rudder and the cockpit cowl when open.

The hangar design concepts are listed below, beginning with the original proposal.

B. SELF-RIGIDIZED STRUCTURES

1.) Design Concept (Figures 44, 45)

The proposal concept for a hangar for L-28 aircraft was a rigidized framework with an attached skin. The frame would be made of non-rigid plastic skins, zipped together to form tubes. The tubes would be filled with a self-foaming plastic, shipped in a dry state as a micro-encapsulated "powder".[1] The self-foaming plastic would be activated by electric heat. When completely foamed to fill the tube, the plastic would rigidize thereby rigidizing the tubes or ribs of the framework.

The attached skin between the tubes or ribs would be pulled tight to stabilize the structure and to act as weather protection.

2.) Summary

The hangar would meet and, in several conditions, surpass the goals and requirements set forth in the original guiding principles.

The concept seemed to be a satisfactory proposal from all standpoints except one, this being the greatest hurdle at the present time. The point which stopped the proposal was that the state of the art of self-foaming plastics was not sufficiently advanced to facilitate development of the concept into test models and actual mock-ups.

The concept is considered by the research team to be worthy of future investigation when further development of self-foaming plastics has been accomplished.

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[1] Process of micro-encapsulation of liquids developed by the National Cash Register Company, Dayton, Ohio.

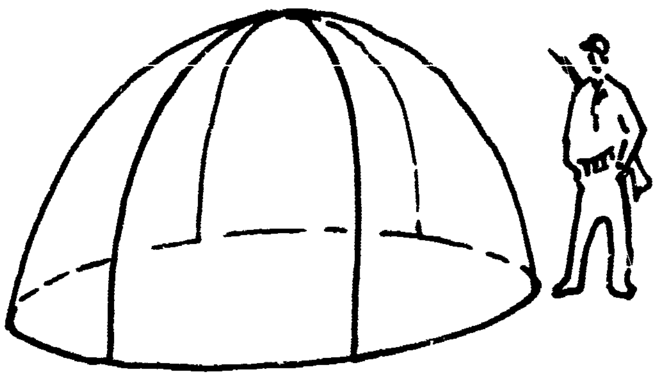


FIGURE A.

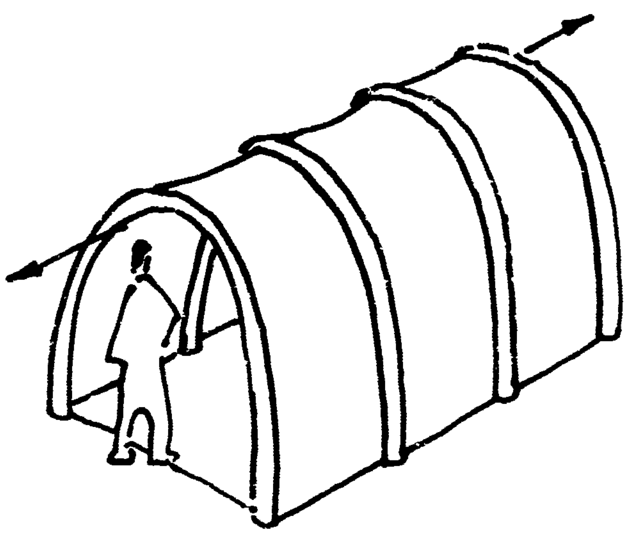


FIGURE B.

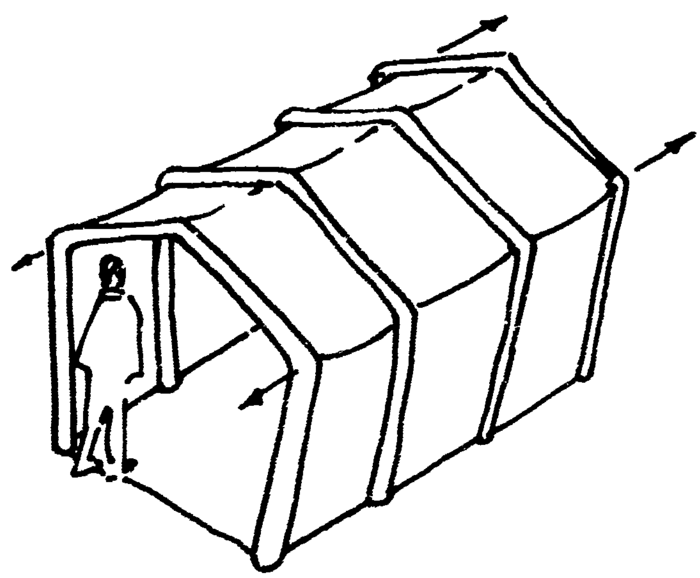


FIGURE C.

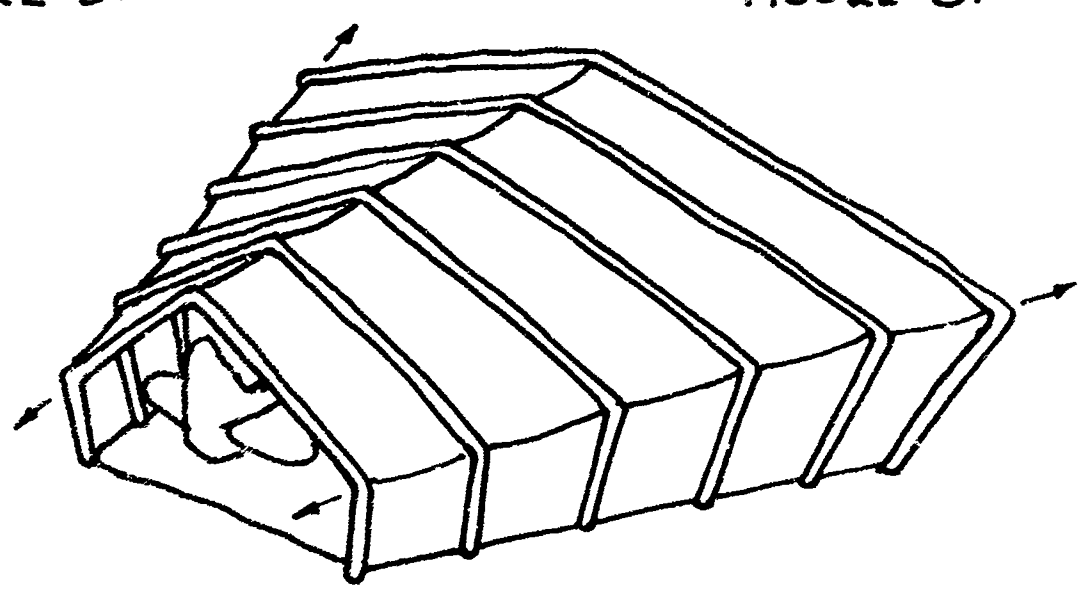


FIGURE D.

FIGURE 44.
VIEWS OF SELF-RIGIDIZING SHELTERS

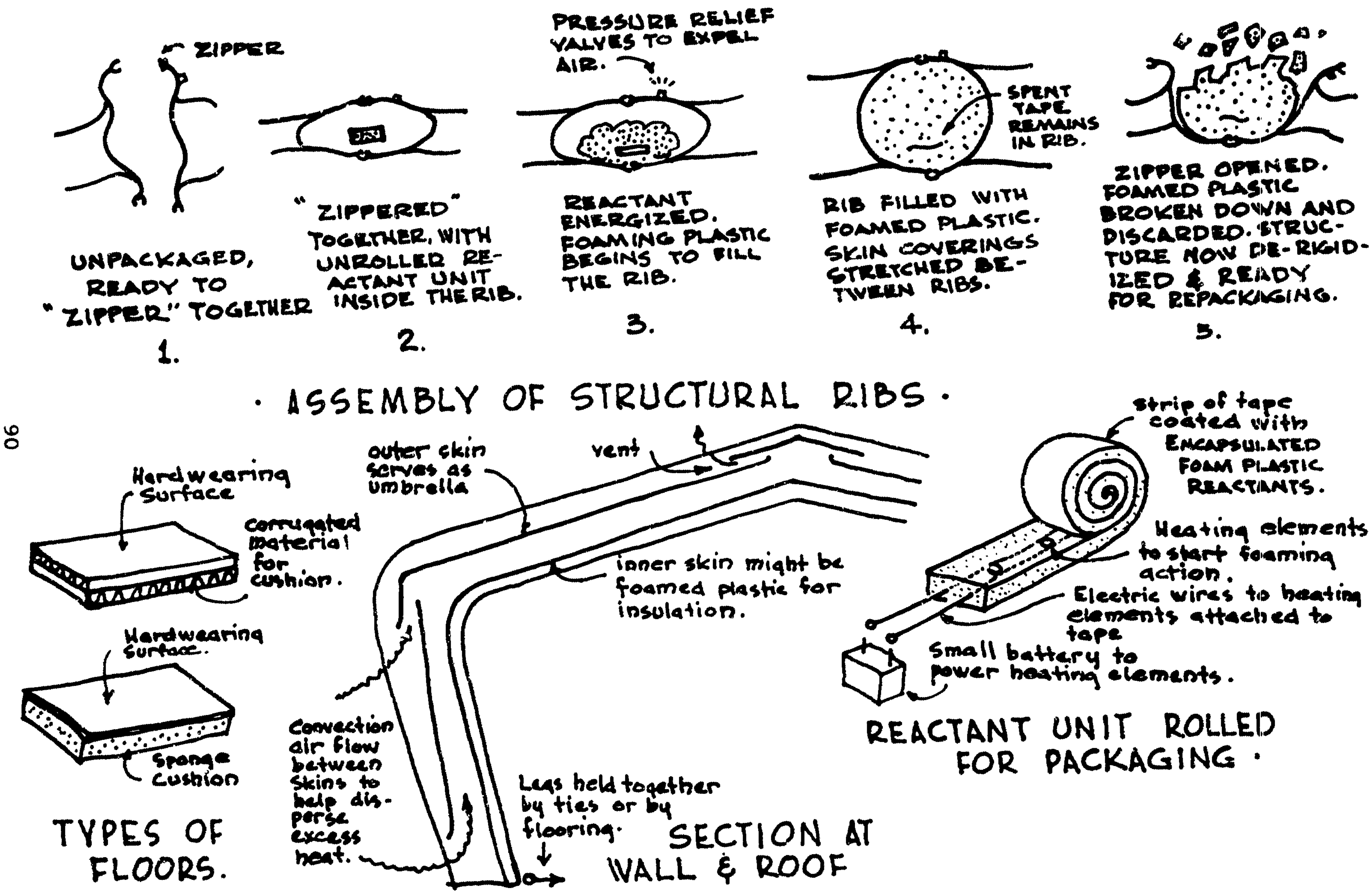


FIGURE 45. DETAILS OF SELF-RIGIDIZING SHELTERS

C. TRAPEZOIDAL ROD- OR TUBE-FRAMED ARCHES

1.) Rod-Framed Arches

a.) Design Concept (Figure 46)

Trapezoidal-shaped frames made of welded rods would be hinged together in pairs with tie rods. The pair would be capable of extending into a flat position for packaging. When rotated about the hinges, the pair of frames would close together to form a "keystone"-shaped triangular unit. This unit would be the basic module of the structure.

A number of "keystone" units would be connected together to form a segmental arch with a triangular section. Arches would be set up vertically at regular intervals along the longitudinal axis of the hangar and would be held in position by purlins and wind braces attached to the arches.

A weather protection skin of insulated fabric or interlocking rigid or semi-rigid panels would be attached to the underside of the barrel-vault or would be stretched or laid over the structure.

Fabric doors would be installed at the ends of the structure.

b.) Structure

The "keystone" module would be about 3 feet long and would be braced by diagonal members to keep the L/R ratio down for the members of the unit. The arches, being of a segmental type with a triangular section and being made up of welded rods, would in essence be arched trusses so interconnected as to become almost a "space-frame". The outward thrust at the base would be taken by anchors set in the ground or by tension cables across the base.

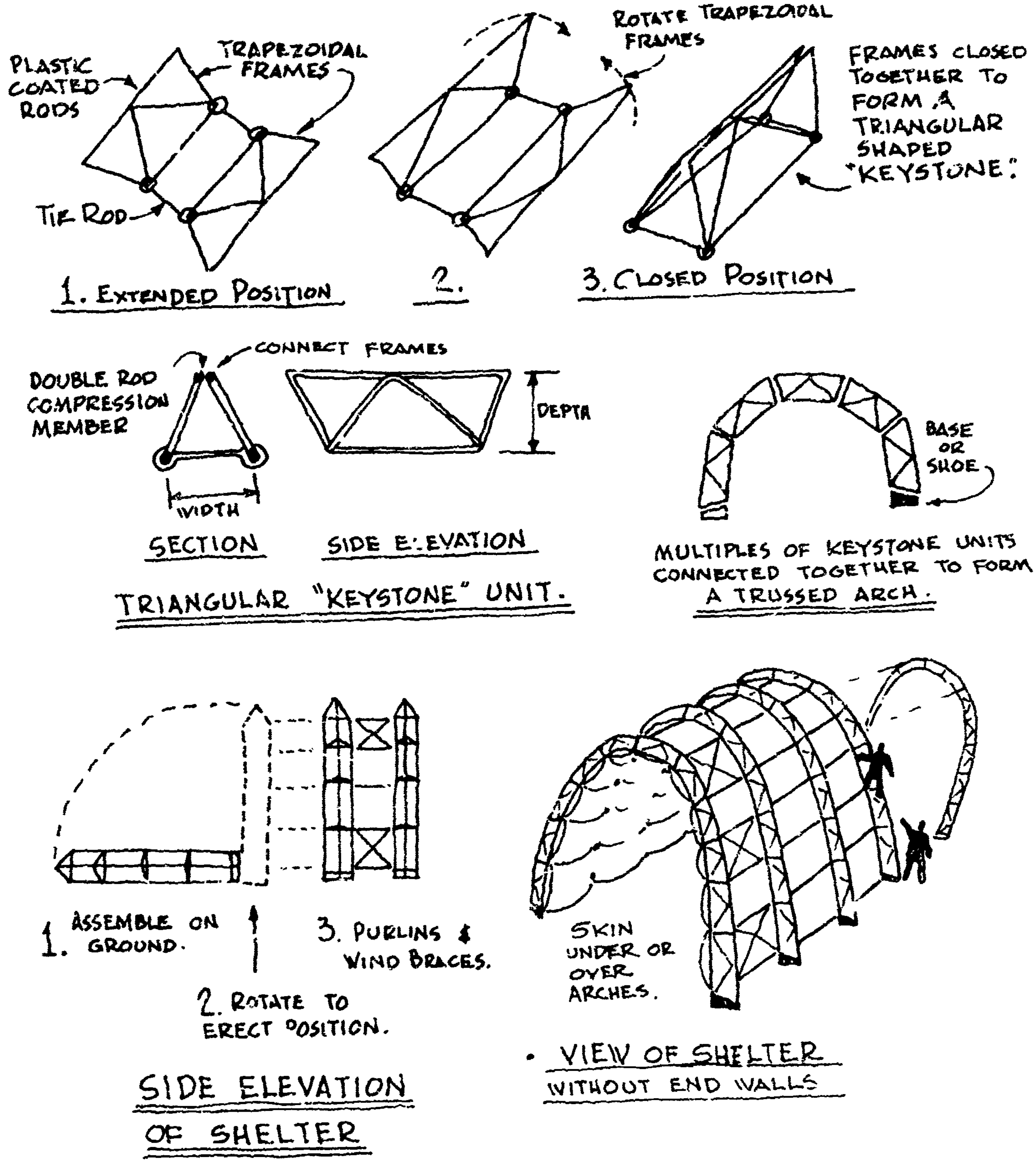


FIGURE 46. TRAPEZOIDAL ROD FRAMED ARCH

c.) Materials

The arches would be made of aluminum or magnesium rods of diameters as necessary to act as columns to take compressive forces in the arch. The skin could be of neoprene-coated nylon fabric or other similar fabric with flexible foamed polyurethane laminated to the underside. A durable fabric wearing surface could be laminated to the interior side of the skin. Fome-Cor, as used in the small shelter, could be used as a rigid board skin.

d.) Details

The rods would be bent to form loops which would serve as hinges for folding or rotating the trapezoidal frames to make up the "keystone" modules. The modules would be clipped together with metal ties or clips applied with heavy duty pliers.

The ends of the purlins and wind braces would be flattened so they could be looped or bent around the rods of the arches.

The fabric skin would have tapes sewn to the fabric at intervals to match the spacing of members of the circles and purlins. The tapes would serve as ties to secure the fabric to the framework. One section of fabric would fit transversely and would be fastened to two or three arches. Transverse joints might be snapped together and be equipped with a weatherproof type gasket, or might be zippered for weatherproofing.

Weatherproofed "Fome-Cor" board with scored and folded interlocking flashed ends could be tied by tapes to the underside of the arches. The flashing would occur along joints in the longitudinal direction of the hangar. Transverse joints would have foam plastic weather stripping.

e.) Packaging, Shipping

The trapezoidal frames would be laid out flat and would be stacked and strapped on a pallet, together with enough purlins and wind braces to construct one arch.

The fabric skins would be rolled or folded into bundles, or, the rigid board panels would be unfolded, laid out flat and would be stacked and strapped into packages (or on pallets) sufficient to cover two arches.

Arch bases, shoes, or grade beams would be strapped into packages or bundles.

Anchors, tie cables, etc., would be packaged in cartons, coils, etc.

All packages, bundles, and cartons would be of sizes which could be handled by a maximum of four men.

f.) Erection Procedures

The trapezoidal frames would be folded by hand into "keystone" units or modules. The modules would be clipped together into arches lying on their sides on the ground. The first two arches would be assembled while lying with their bases almost touching. Spacing at the basis could be accomplished by positioning the arches on a grade beam. The arches would be rotated upward simultaneously and would be clipped together with purlins and cross braces in order to achieve some degree of stability during the first stages of erection.

Fork lift trucks, jeeps, blocks and tackle, (or possibly a crane) would be used as equipment for setting the arches in an upright position.

Successive arches could be assembled on the ground and rotated upward into position. Each successive arch would be locked to the upright frame with purlins and braces to hold the structure in position.

The structure would have an adequate number of closely spaced intersecting rods so that no extra ladders would be needed, and the erection crew could climb the frame for above-the-ground work.

The fabric or the panels would be hauled by rope up to the frame. The attachment tapes would be hand tied to the frame.

g.) Model (Figure 47)

A 1/3 size model of a pair of rod framed arches (about 17' wide and 8 1/2' high) was constructed.

The frames were made of 1/8" welding rod, and were about 1' long. Twenty-seven modules made up one arch.

The modules were wired together at the intersecting points, where clips might be used on a full-size module. Rod purlins and wind braces with hooked ends were clipped over the rods of the arches to lock the two arches together.

Panels of corrugated cardboard were scored and folded to form interlocking flashing at the joints between adjoining panels. The panels were equipped with tie tapes and were attached to the arches. The tighter the panels were pulled against the arches with the ties, the closer the fit at the flashing folds.

h.) Summary

No special tests were run on the rod framed arched trusses, but visual observation and some measurements showed a need for a more positive method of positioning adjoining "keystone" modules. Wiring or clipping the modules together permitted the rods to ride past each other and transfer all stresses to the wire or clips. The wires or clips would not be adequate to carry stresses such as those in the rods of the frames.

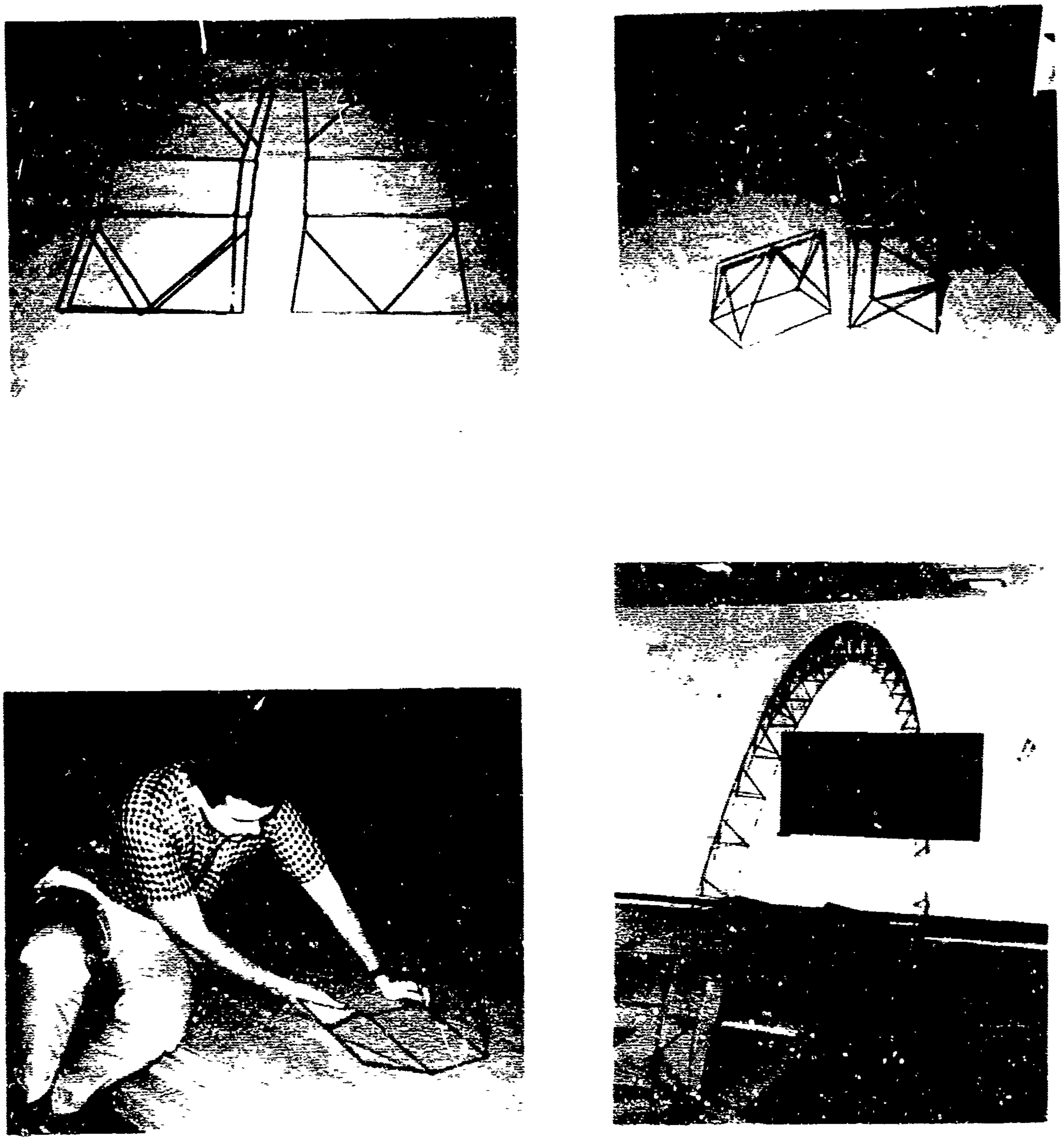


FIGURE 47. MODEL OF ROD FRAMED ARCH (MODULE UNFOLDED, ERECTION PROCEDURES, COMPLETE ARCH)

The displacement of the adjoining modules in the arch caused the arch to deform or to go out of alignment. Further study of the trapezoidal framed arch concept followed.

2.) <u>Tube Framed Arches</u>

a.) Design Concept (Figure 48)

The concept was essentially the same as the "Rod Framed Arch" described above. Investigation of weights of steel and aluminum rods, relative strengths of other structural shapes, complexity of fabrication and erection, numerous connections, and methods of positive transfer of stresses through the structural members, led to a concept of using lightweight metal tubes in place of rods.

Two trapezoidal frames would be hinged about a common long side member of the trapezoids. The frames would be rotated on their common hinge line and would be secured in a triangular "keystone" module shape by a combination spacer-and-purlin. The modules would be pinned together to form an arch.

The weather protection skin, and doors would be similar to those described in the rod framed arch concept.

b.) Structure

The structural system would be similar to the rod framed arch.

c.) Materials

The members of the trapezoidal frames and the spacer-purlins would be aluminum tubes. The size of the module would be about 6' long. (Twelve modules make an arch 50 feet in span, thereby reducing the number of connections by more than one half of those for the rod framed arch.) The longest members of the frame which might carry compressive stresses

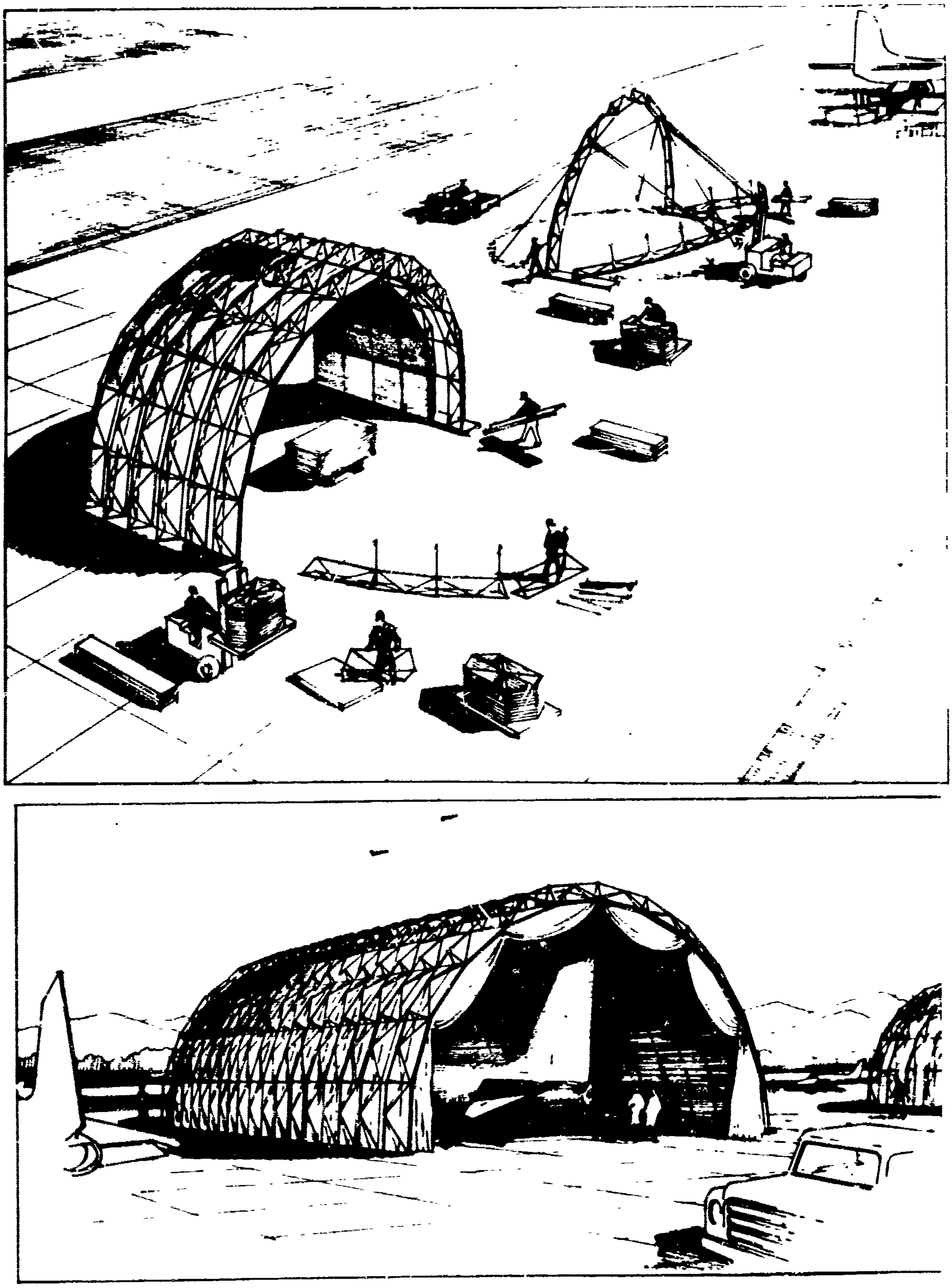


FIGURE 48. VIEWS OF ERECTION OPERATIONS AND COMPLETED TUBE FRAMED ARCH HANGAR

required aluminum tubing 1.25" O.D. with 1.8" wall thickness and weighing 0.520 lbs per foot. Grade beams could be magnesium-aluminum alloy structural or fabricated shapes. Other materials could be similar to those previously described.

d.) Details

The top and bottom chords of the trapezoidal frames would be of tubes. The diagonal braces of the frames would be tubes or rods, depending on the magnitude and nature of the stresses. The tube chords would have swaged ends to slip into tube ends of adjoining modules. Other solutions for this joint were 1) clevis ends joined by pins, 2) offset angle ends bolted together, 3) cam type hooks to latch over keepers or bars, and 4) sleeves across joints.

Some of the same joining methods could be used for attaching the spacer-purlins to the arches. The grade beams would have interlocking lugs which could be slipped together at an angle and dropped into place for locking. Other details would be similar to those previously described.

e.) Packaging, Shipping and Erection

The methods previously described might also be used in this concept.

f.) Summary

No models of this concept were built, but the study development appeared to have many improvements over the rod-framed arch concept.

The number of modules was reduced; the spacers were combined with the purlins; the number of connections was greatly reduced; the connections were made more positive and accurately aligned for transferring stresses;

the tubular sections increased the strength and lowered the weight as well as making possible the larger modules.

Preliminary weight studies showed about 650 lbs per arch. With closer calculations on weights of arch members this was later cut to about 400 lbs/arch.

Preliminary cost estimates for constructing an experimental prototype hangar 50' x 80' x 25' high, including the structural frame, skin, and end doors, was between $75,000 and $100,000 as of October 1964.

D. ARCHED BEAM CONCEPT

1.) Design Concept (Figure 49)

The structural frame for this concept would be made of "I" beams or "T" beams with the upper flanges doubled. The doubled upper flanges would be spaced apart the dimension of the thickness of the skin material. The skin material would be an almost rigid panel and would be installed in shingle fashion in the grooves of the upper flanges of the beams.

The beams would be bent in a curve to make a 50' arch 25' high. (The same principle could be used to make a 16' arch 8' high for the small shelter.)

Purlins or spacer angles or tubes would be inserted in slots in the beams and then rotated to lock them securely be wedging tongues in the slots. These purlins would space the beams apart as well as pull the beams toward each other thereby locking the panels in the grooves.

The lower ends of the beams would sit in slots in grade beams staked to the ground.

2.) Structure

The structural system involved would be a conventional circular arched rib of special beam section, with purlins spacing the ribs apart and

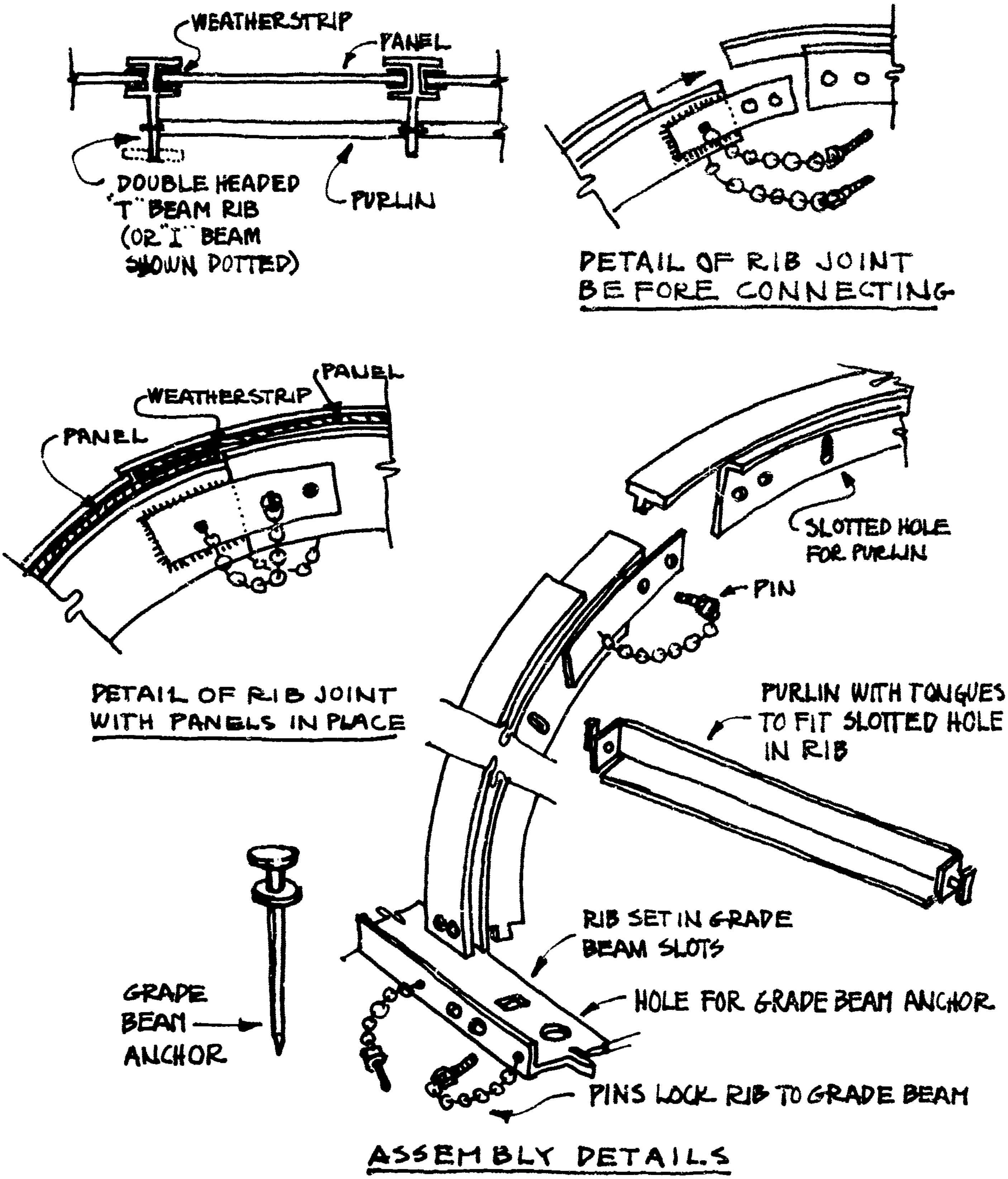


FIGURE 49. ARCHED BEAM HANGAR CONCEPT

making the structure stand upright. Additional diagonal cross bracing would be necessary to prevent racking.

3.) Materials

The ribs would be of aluminum or magnesium alloy, extruded in a special structural form, and would be bent into a curved shape. The shaping would require some stress relief so as not to overstress the final structure.

The purlins or spacers and grade beams would be aluminum or magnesium alloy.

Splice plates, connectors, pins, etc., would be of similar materials.

The panels would be of weather-proofed Fome-Cor board, or other insulating type board, if the ribs and/or purlins were not spaced more than 2' to 3' apart. (The Fome-Cor begins to sag at these spans under its own weight when exposed to the weather, particularly sun.) The panels would be of weather-proofed honeycomb or other reinforced structural type material if the ribs and/or purlins were spaced 3' to 8' apart.

The overlapping edges of the panels would be weather stripped as well as being installed in shingle fashion.

The side edges of the panels which slip into the grooves in the ribs would be weather stripped with a compressible material that would slide readily into the grooves.

4.) Details

The curved beam would be cut in lengths for easy handling and packaging. The sections would be joined in the field with locator pins and bolts or lock pins.

The crown piece of the arch would have the ends cut with the upper flange of the double head extending beyond the joint line. The piece of the arch adjoining the crown piece would have its upper flange cut shorter than the joint line. This undercut would fit, shingle fashion, under the overhanging flange of the crown piece. Each succeeding joint down the remainder of the arch would have the flanges cut similarly to overlap. The overlap of the panels would occur at the same point.

The connector for the purlin would be a stud with a "T" head which would slip through a slotted hole in the web of the arch beam. The purlin would be rotated thus locking it to the arch beam.

5.) Packaging and Shipping

Metal parts would be strapped together in packages to make up one arch. Panels would be stacked flat and strapped to pallets. Small parts would be packed in cartons.

6.) Erection

The first arch would be assembled flat on the ground. Purlins would be set into the slots of the first arch. Panels would be inserted into the grooves of the first arch.

The second arch would be assembled and set on the upright purlins and the grooves would engage the panels. The purlins would be rotated to lock the two arches together.

The two-arch assembly, with panels in place between them, would be set up in position on the grade beams. From this stage on, succeeding panels and framing would be added to the structure, starting at the ground level and building upward to the crown.

7.) Summary

No models of this concept were built. The structural system is of such a conventional nature that sizing the members should pose no major problem.

The main design problems would involve the connectors and the weather proofing and sealing.

E. THREE-HINGED ARCH CONCEPT

1.) Design Concept (Figure 50)

Two legs of a three-hinged arch would be assembled on the ground and would be hinged at their apex. The outer (lower) points of the three-hinged arch would be tied together with a cable or strap. Tension applied to the cable would draw the lower points together and would raise the center hinge point. Additional arches would be erected in a similar manner, and would be locked together with purlins and wind bracing.

A skin similar to others previously described would be applied on or under the skeleton to provide weather protection.

2.) Structure

The structural system is a conventional three-hinged arch.

3.) Materials

The metal parts would be aluminum or magnesium tubes or structural shapes for the truss members and tracks, and sand castings for hinge points or other special connectors. Cables would be steel. The flexible skins of fabric and/or the panels of "Fome-Cor" or honeycomb core, and the end doors would be similar to those previously described.

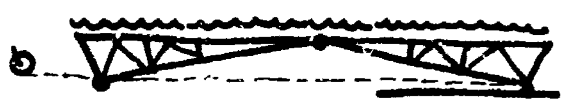
X-2 THREE HINGED ARCH.

TRUSSES SHIPPED K.D. UNPACK, FIELD CONNECT WITH PINS TO FORM THE TWO PARTS OF A THREE HINGED ARCH.

1.

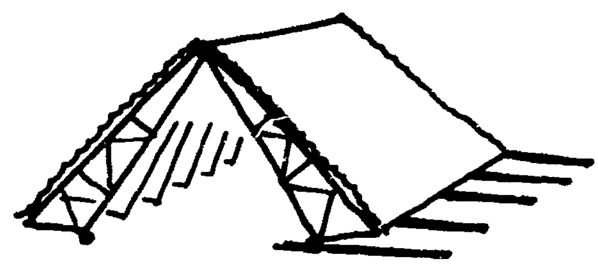
TRUSS PARTS FASTENED TOGETHER. CENTER HINGE POINT BLOCKED UP. LEFT HINGE POINT ANCHORED TO PREVENT SLIDING. RIGHT HINGE POINT SET IN TRACK TO PERMIT SLIDING. RIGHT & LEFT HINGE POINTS CONNECTED BY CABLE.

2.



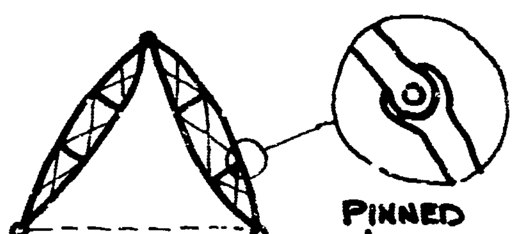
SKIN OR PANELIZED COVER APPLIED ACROSS TOPS OF TRUSSES. WINCHES PULL CABLES CAUSING RIGHT HINGE POINT TO SLIDE IN TRACK TOWARD THE LEFT HINGE.

3.

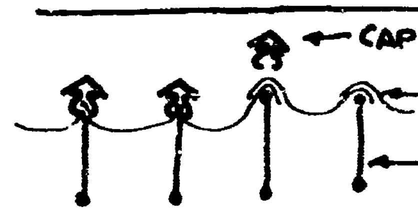


CABLES PULL ARCHES INTO FINAL POSITION. ENDS CLOSED BY DRAPED FABRIC DOORS.

4.



CURVED CHORDS ON TRUSS MAKE TRUSS PARTS MORE INTERCHANGEABLE.



CAP STRIP WITH CLAMPS COVER JOINTS OF FABRIC AS FLASHING, AND ALSO ANCHOR FABRIC TO ARCHES.

PANEL OR SKIN COVERS.

FIGURE 50.
THREE-HINGED ARCH

4.) Details

The truss parts would be subassembled into short lengths. These subassemblies would be pinned together in the field to form the two parts of the arch. The connections would be clevis type with bolts or lock pins. The trusses could be of conventional triangular shape, or they could be curved chord trusses so more parts of the trusses might be interchangeable.

The lower points of the arch would be provided with shoes; one to be anchored to the ground; the other to slide or roll in a track. The track would be anchored to the ground and would have a locking device to hold the lower point of the arch in its final or erected position.

Panels for the roof could be detailed and installed similar to others previously described, or could be set diagonally from the upper chord of one truss to the lower chord of the next truss. The chords of the trusses would be equipped with grooves and shelf-type supports arranged to hold the panels and at the same time to serve as flashings along the ridge and valleys.

Fabric skins might be as previously described, or might be in strips laid transversely across the hangar with the edges of the strips overlapped along the upper chord of the truss. Metal cap flashing strips with a clamp attachment to fit over the truss chord members would be clamped over the fabric to secure it to the truss.

5.) Packaging, Shipping, Erection

Packaging and shipping techniques would be similar to others previously described.

Erection would be accomplished from the ground. The trusses would be assembled and pinned together on the ground. The one end of a truss would be anchored to the ground; the other end would be set in the track. The two lower ends would be tied together with a cable.

The center point of the arch would be jacked up slightly above grade to assure the center hinge being above the tension cable to facilitate the arching action. Tension would be applied to the cable with winches thereby raising the arch. Trusses might be pulled up individually, or the entire framework of the hangar might be assembled on the ground (even to installing the skin material) and with a series of cables and synchronized winches the complete structure might be raised in one operation.

6.) Summary

No models of the concept were built. An investigation of weights of magnesium, aluminum, and fiberglass used in frames comparable in size to the proposed trusses indicated that one arch might weigh about 130 pounds. The total weight including arches, covering, ends, cross bracing, cables, and incidentals, was estimated at about 6000 pounds.

F. SHELL ARCH CONCEPT

1.) Design concept (Figure 51)

Units of a rigid plastic or sheet metal, with some surface modulation for additional stiffness, would be connected together at sides and ends. The units would be assembled on the ground in a horizontal position. One edge of the completely assembled group of units would be securely anchored to the ground. The other edge would be set in tracks. The two edges would have been tied together with cables. Tension applied to the cables would cause the structure to bow or arch itself into a curved shell.

2.) Structure

The curved shell might be compared to the simple bow; the curved plate being the arch and the cables being the bow strings.

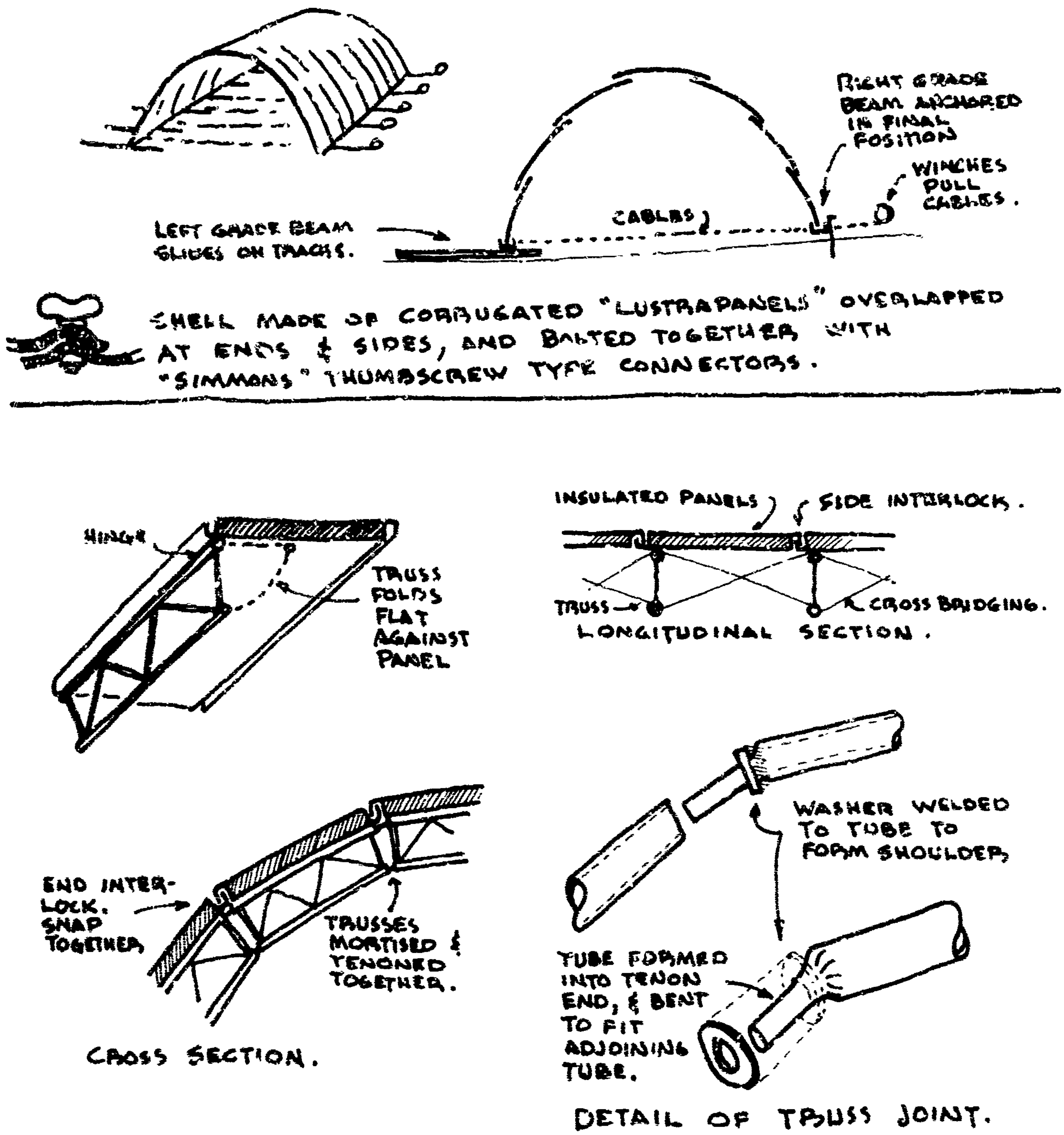


FIGURE 51. COMPRESSION (SHELL) ARCH AND COMBINATION TRUSS AND ARCH

3) Materials

The plates might be of U.S. Royalite, corrugated Lustrepanel, corrugated aluminum or other similar materials.

4.) Details

The panels would be lapped at the sides and ends and would be connected by Simmons thumbscrew type fasteners or similar devices.

5.) Packaging, Shipping, Erection

The panels would be stacked and strapped into bundles for shipping. Erection would be similar to the methods described under the three-hinged arch, in that winches would pull the cables and erect the structure without the use of cranes.

6.) Summary

No models of this concept were built. A brief investigation of weights for this hangar made of Lustrapanel indicated that the total weight of the shell, cables, end cables, and incidentals might be about 8000 pounds. Erection time for a crew of seven was estimated at about five hours.

G. COMBINATION TRUSS AND PANEL ARCH CONCEPT

1.) Design concept (Figure ..)

Rigid panels with interlocking sides and ends would be equipped with "bar-joist" type trusses mounted under the panel. The truss would fold flat against the panel for packaging. The truss would be set upright and joined to trusses of adjoining modules to form a trussed arch with an integral skin.

2.) Structure

The truss units would form an arch. The arches would be laterally braced by the panels and cross bridging.

3.) Materials

The metal trusses would be of aluminum of magnesium. The panels would be of U.S. Royalite, honeycomb core, or other similar rigid, insulated, panel or board.

4.) Details

The panels would have grooves along the edges and ends, arranged to interlock with grooves of adjoining panels. The grooves would be weather stripped and would be self-draining from one panel to the adjoining downhill panel. The ends of the truss units would have swaged tenons to fit in the adjoining truss ends.

5.) Packaging, Shipping, Erection

The trusses and panels would lay flat for each stacking and packing for shipment. Erection would probably require the use of lift trucks or mobile ladder trucks so that panels might be placed in position above the ground level.

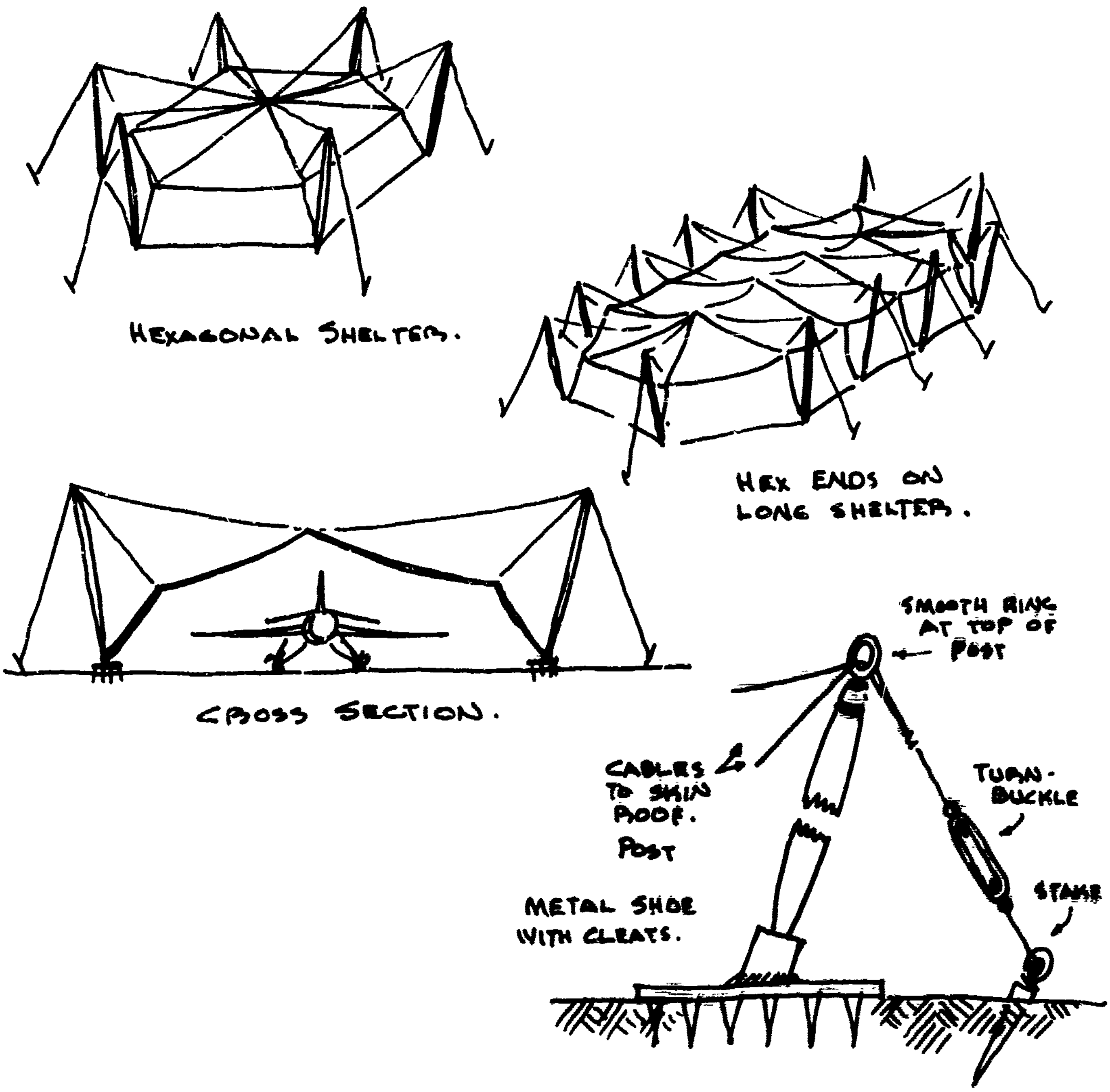
6.) Summary

No models or weight studies of this concept were made.

H. TENSION STRUCTURES

1.) Design concepts (Figure 52)

Several tension structures were studied. One proposed structure would be of fabric suspended by a series of cables from poles located around the exterior perimeter of the shelter. Another would be a fabric skin suspended from a large, lightweight metal compression ring pulled into a hyperbolic paraboloid shape by tension cables tied across the diameter of the ring.



X-6 LIGHTER-THAN-AIR STRUCTURE

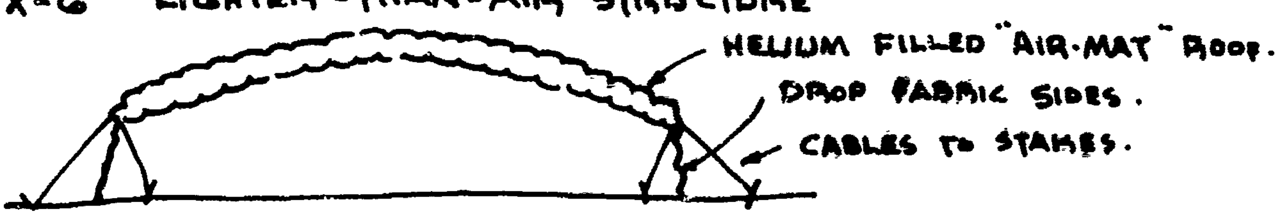


FIGURE 52. TENSION STRUCTURE, LIGHTER-THAN-AIR STRUCTURE

2.) Summary

Tension structures of tent-like appearance could be very lightweight and small package size. Many of the modern fabrics and sheets are extremely strong and durable, so the weight/strength ratios are high. However, by direction of TAC recommendations such concepts were not investigated deeply because other agencies have conducted extensive research and development in these areas.

I. LIGHTER-THAN-AIR STRUCTURES

1.) Design concepts (Figure 52)

Gas-inflated balloon type structures, and also pressurized balloon structures, were considered in a casual way.

2.) Summary

Concepts of these types were not carried further because of the reasons stated in paragraph H2.

J. SPACE FRAME STRUCTURES

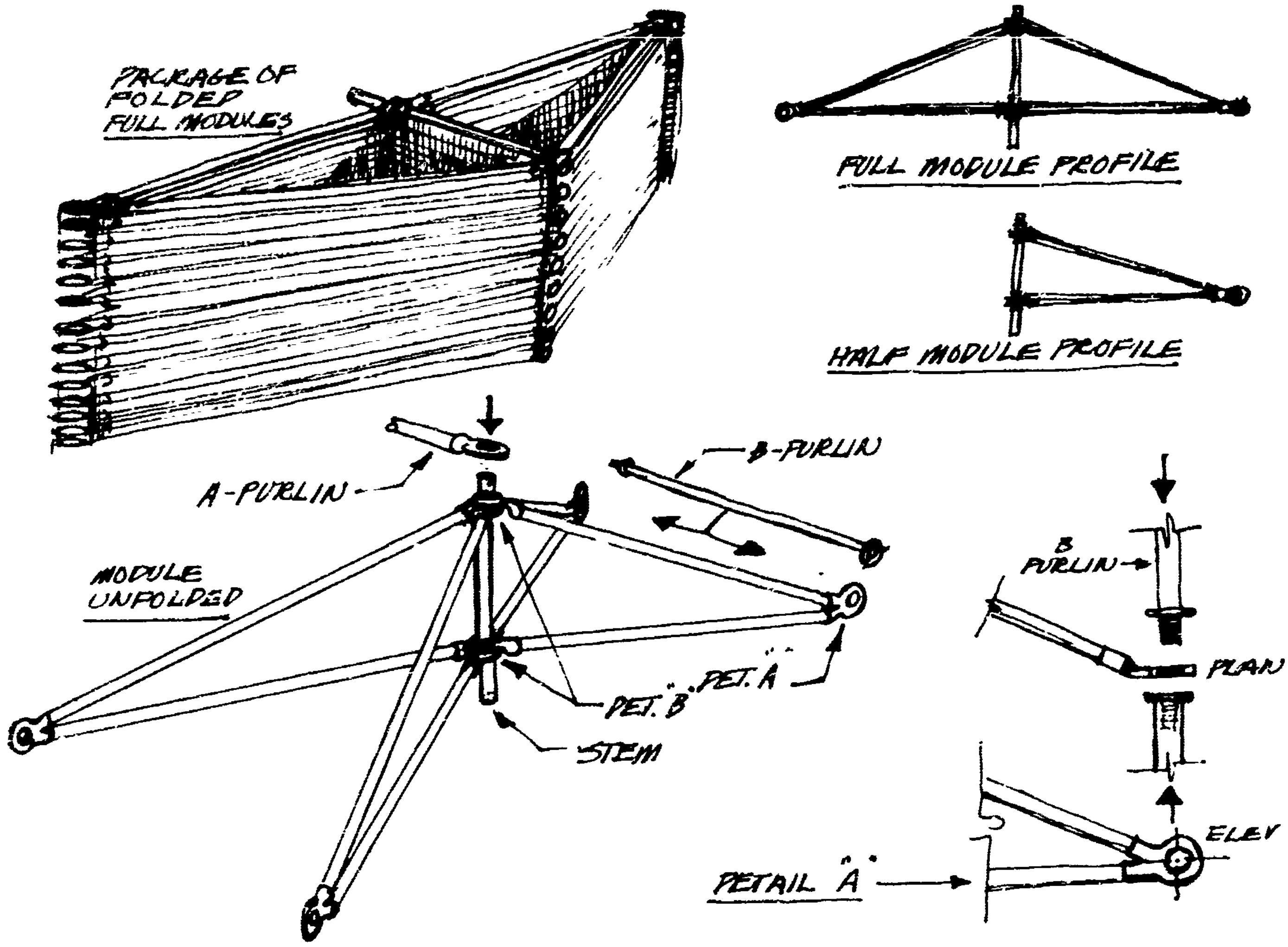
1.) Design concept (Figures 53, 54, 55)

Interacting tubular framework in a geometric configuration resulting in a curved-plane space frame of barrel vault shape would be made of short lengths of tubing. The frame would be made up of a number of star-shaped subassemblies, or modules, connected together by purlins running longitudinally and by lower chord members running transversely across the shelter.

Fabric skins or rigid panels would be used to enclose the shelter. End doors of fabric would be suspended from the frame.

2.) Structure

Each star-shaped module is made up of two pairs of dissimilar tetrahedrons. When a module is connected to an adjoining module with purlins,



STRUCTURAL COMPONENTS OF THE MODULE ARE TUBULAR LIGHTWEIGHT METAL WITH CAST OR FORMED END FITTINGS. MODULE FOLDS IN A SCISSORS FASHION, PIVOTING ABOUT THE STEM. PURLINS JOIN MODULE TO MODULE IN A FLATTENED ARCH FORM. APPLICATION OF CHORDS FROM STEM TO STEM PRODUCES ROUNDED ARCH. (SEE ERECTION SEQUENCE.)

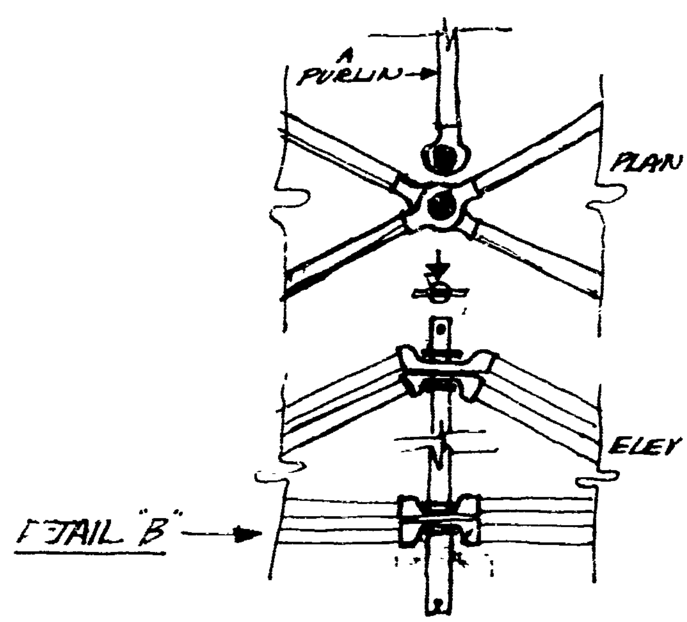


FIGURE 53. SPACE FRAME, MODULES

ERECTION SEQUENCE

FIVE FULL MODUES & TWO HALF MODULES COMPRISE A SINGE BASIC ARCH FORM.
(1) FOR STABILITY, TWO BASIC ARCHES (10 FULL MOD. & 4 HALF MOD.) ARE ASSEMBLED ON GROUND. PURLINS & GRADE BEAMS ARE ATTACHED. THIS IS ONE BUILDING UNIT.
(2) ELEVATION AT END OF STEP (1)
(3) CHORD ATTACHED TO STEMS AT FIRST POSITION DRAWS 2ND & 3RD MODULES INTO PARTIAL ARCH.
(4) CONTINUING WITH STEP (3) ACCORDING TO SEQUENCE NOTED IN STEP (2) PRODUCES COMPLETE ARCH.
(5) GRADE BEAMS ARE STAKED DOWN.
REPETITION OF STEPS (1) THRU (5) RESULTS IN 50' × 80' × 25' HIGH HANGAR.

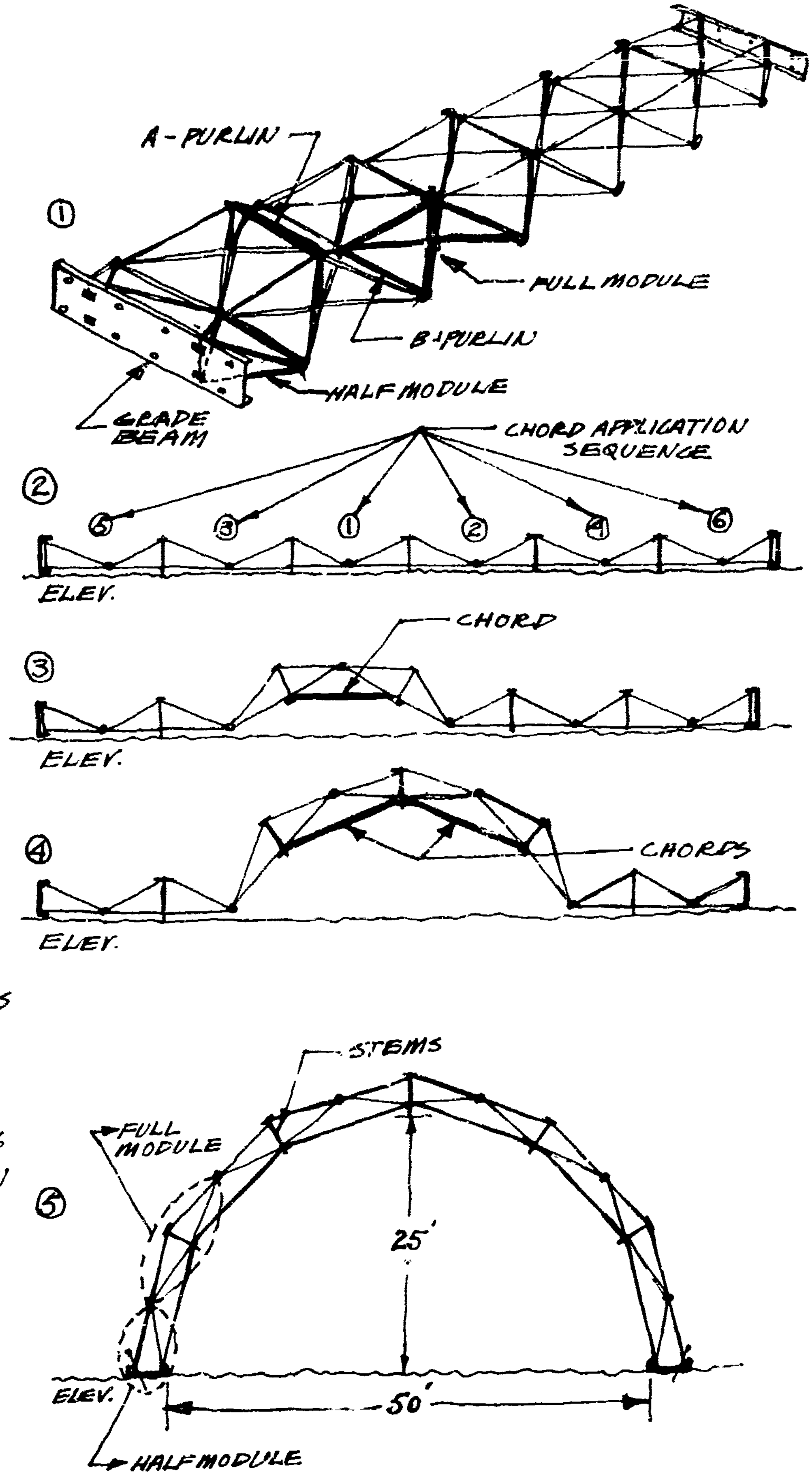
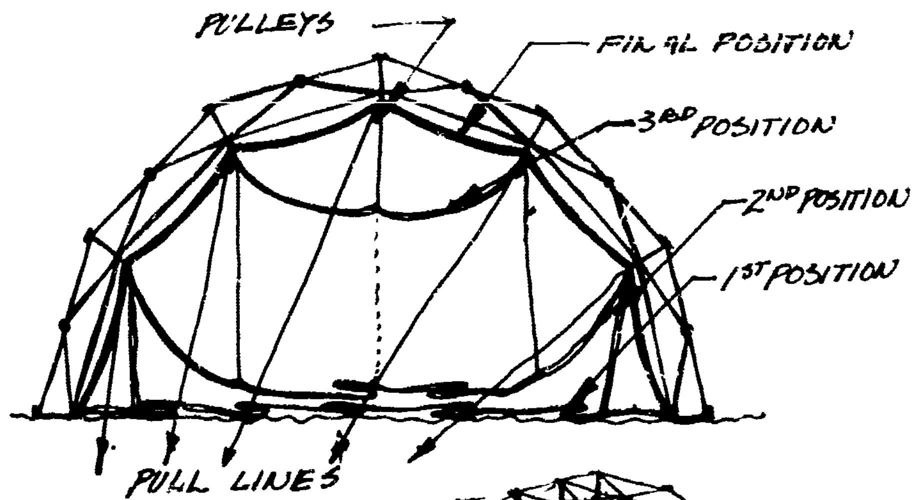
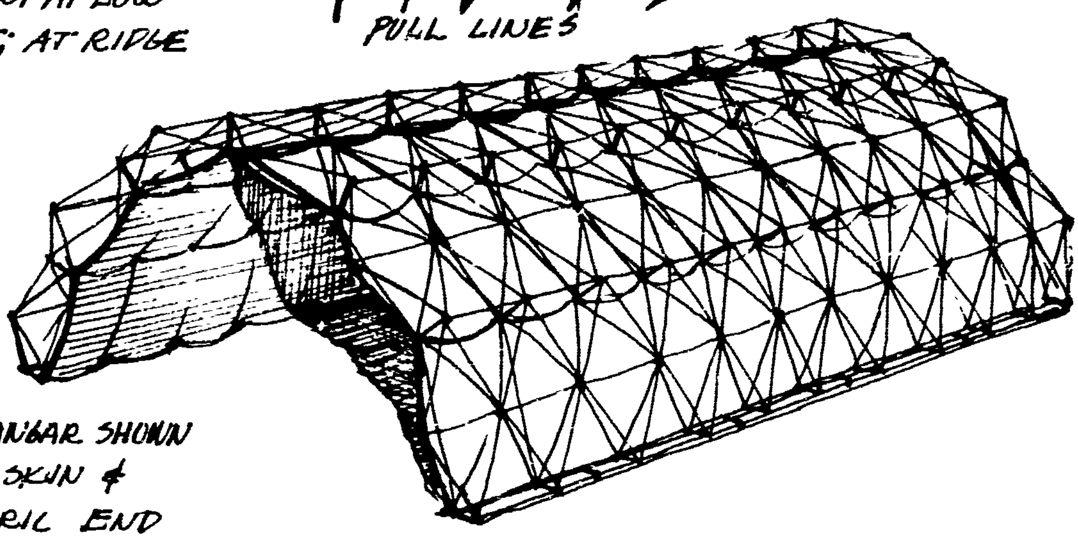


FIGURE 54. SPACE FRAME, ERECTION

FABRIC ATTACHMENT

FABRIC SKIN IS HOISTED IN FOUR STAGES: 1. LAID ON GROUND, LINES FROM SUSPENSION POINTS THRU PULLEYS TO GROUND. 2., 3., & 4. ATTACHMENT AT LOW POINTS FIRST; AT RIDGE LAST.





COMPLETED HANGAR SHOWN WITH FABRIC SKIN & WITHOUT FABRIC END CLOSURES.

RIGID PANELS MAY BE APPLIED IN PLACE OF FABRIC SKIN OR AS INSULATION IN CONJUNCTION WITH FABRIC SKIN. PANELS ARE ATTACHED DURING ERECTION SEQUENCE IN PLACE OF CHORDS. ATTACHMENT IS MADE DIRECTLY TO LOWER ENDS OF STEMS. DESIGN OF PANEL ALLOWS IT TO ACT AS BOTH CLOSURE & STRUCTURAL MEMBER.

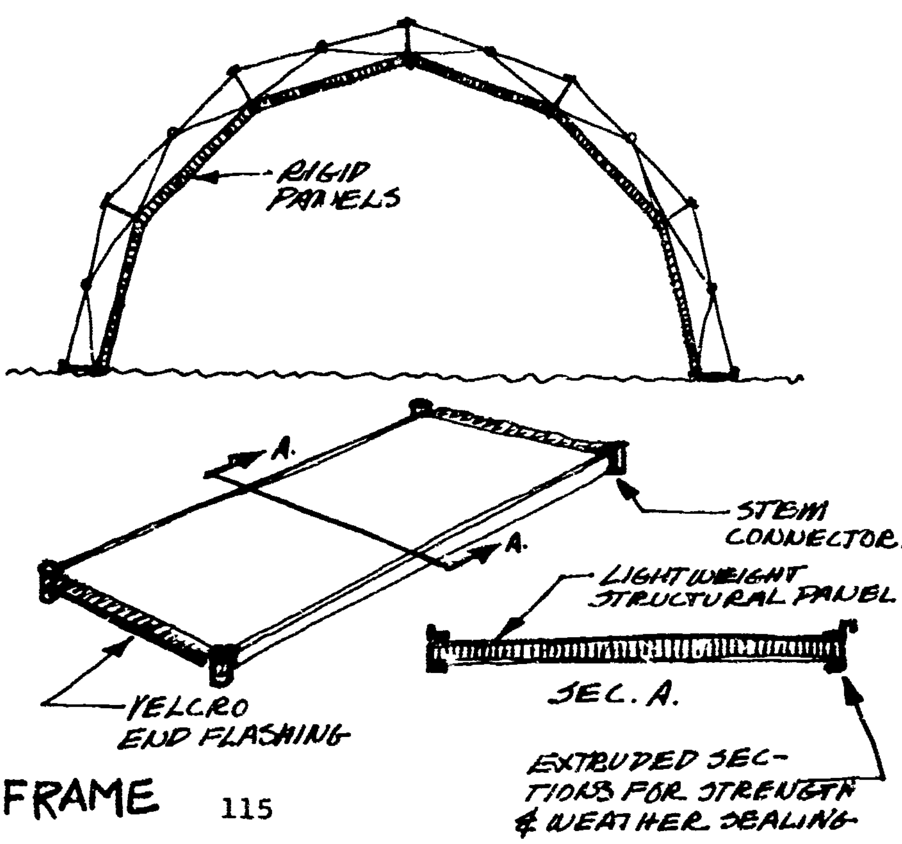


FIGURE 55 SPACE FRAME

the resulting form of that space between the modules is an irregular elongated octahedron. The purlins rigidize the structure in the longitudinal direction of the shelter. The frame is still flexible in the transverse direction to permit further erection from ground level. As the transverse chord members are installed from center to center of the bases of the modules the structure is lifted off the ground and becomes rigid transversely across the arch.

3.) Materials

The metal tubes and case connectors would be of aluminum or magnesium alloy. Fabrics or panels would be similar to other previously described.

4.) Details

Tube ends might be flattened or fitted with cast ends for attaching to other members.

The subassembly or module would be made of four V-shaped parts permanently attached to the center spacer tube or would be made of two elongated diamond-shaped frames which fold scissors fashion about the center spacer tube or stem.

The purlins would be connected by sliding a loop end over the stem and locking with a cotter pin or peg. Purlins spacing the unfolded module would be screwed together through loop ends of the tubes of the module.

Rigid panels could be made of a material such as U.S. Royalite which would be strong enough to take structural stresses. The panels would be fitted with sleeves to fit the stems of the modules in place of the lower chord members.

5.) Packaging, Shipping, and Erection

The modules would be folded flat for packaging and shipping on pallets. Purlins and chords would be strapped in bundles to be carried by one or two men. Fabrics would be rolled in bundles; panels would be stacked.

The modules would be opened or unfolded at the construction site to become the star-shaped unit.

Five full modules and two half modules would be pinned together to form one arch assembly flat on the ground. The lower chord members could be installed in a sequence beginning at the center and moving outward so that the arch could be raised by hand from the ground without the necessity of heavy lifting equipment.

For stability, two arches would be joined together while on the ground and would then be raised as a combined pair.

Additional pairs would be raised in succession and would be connected by means of longitudinal purlins placed after the arches are raised.

6.) Summary

A 3/4" small scale model of the frame (Figure 56) was constructed and measured for manual lifting heights at successive stages of the erection procedure.

No weight, erection time, or cost estimates were made.

The number of modular units was greatly reduced by the relatively large size of the basic unit. The reduction in the number of modules also reduced the number of connections.

Except for the cast metal end connector pieces, the metal parts would be standard commercial items.

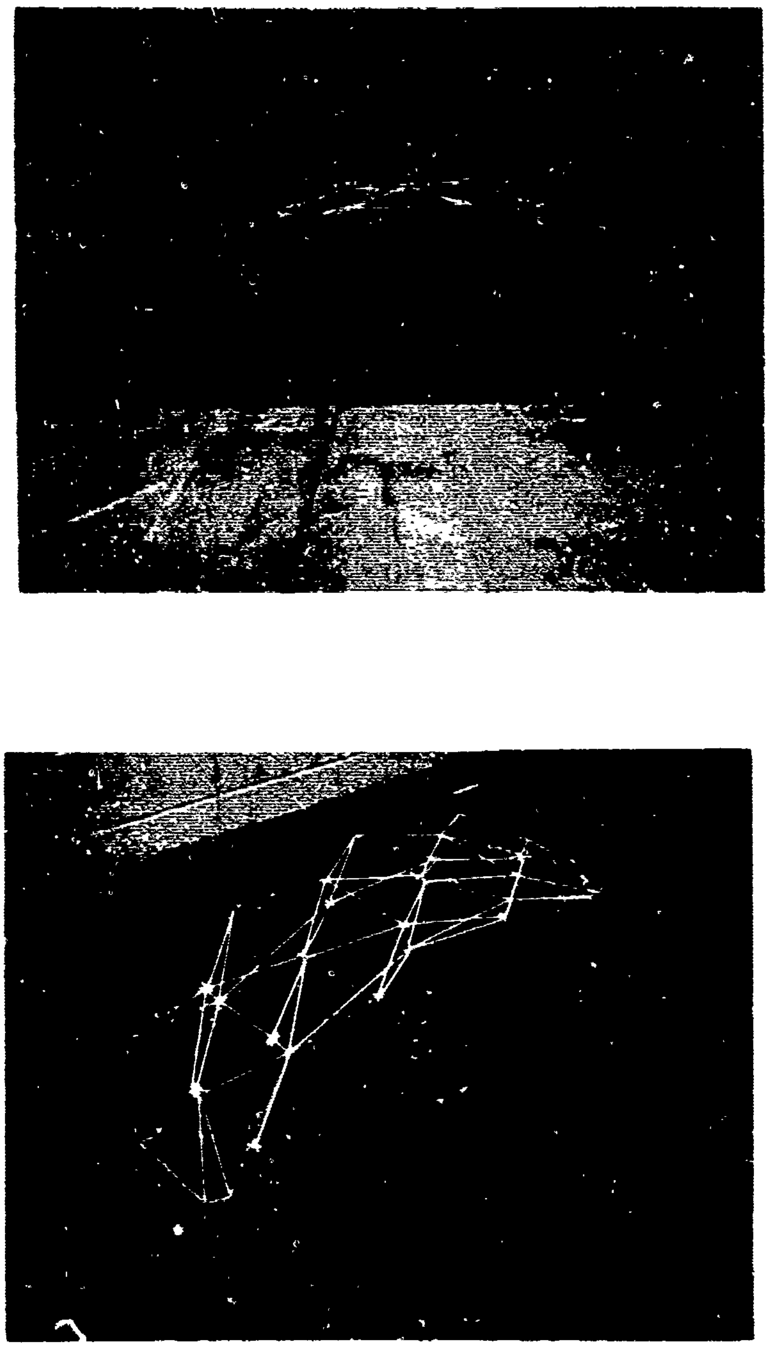


FIGURE 56. MODEL OF SPACE FRAME CONCEPT

K. COMPOSITE PLATE (OR SHELL) WITH LINEAR ELEMENTS

1.) Design concept (Figures 57, 58, 59)

Rigid panels, either flat or curved, set within structural frames of formed sheet metal or of extruded metal shapes would become the primary unit. Units would be interconnected at ground level to form half arches. Two half arches would be pinned together at the apex of what might be compared to the three-hinged arch. The arch would be lifted by tension cables in a manner similar to the three-hinged arch concept.

2.) Structure

The structural system of this concept borrows from the Arched Beam Concept (D), the Three-Hinged Arch Concept (E), and the Shell Arch Concept (F) to become a composite of several of the former concepts.

3.) Materials

The metal parts would be of aluminum or magnesium.

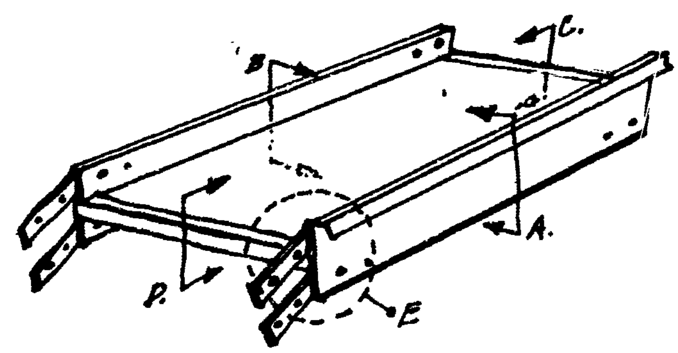
The panels would be of honeycomb or other insulated panel with structural qualities.

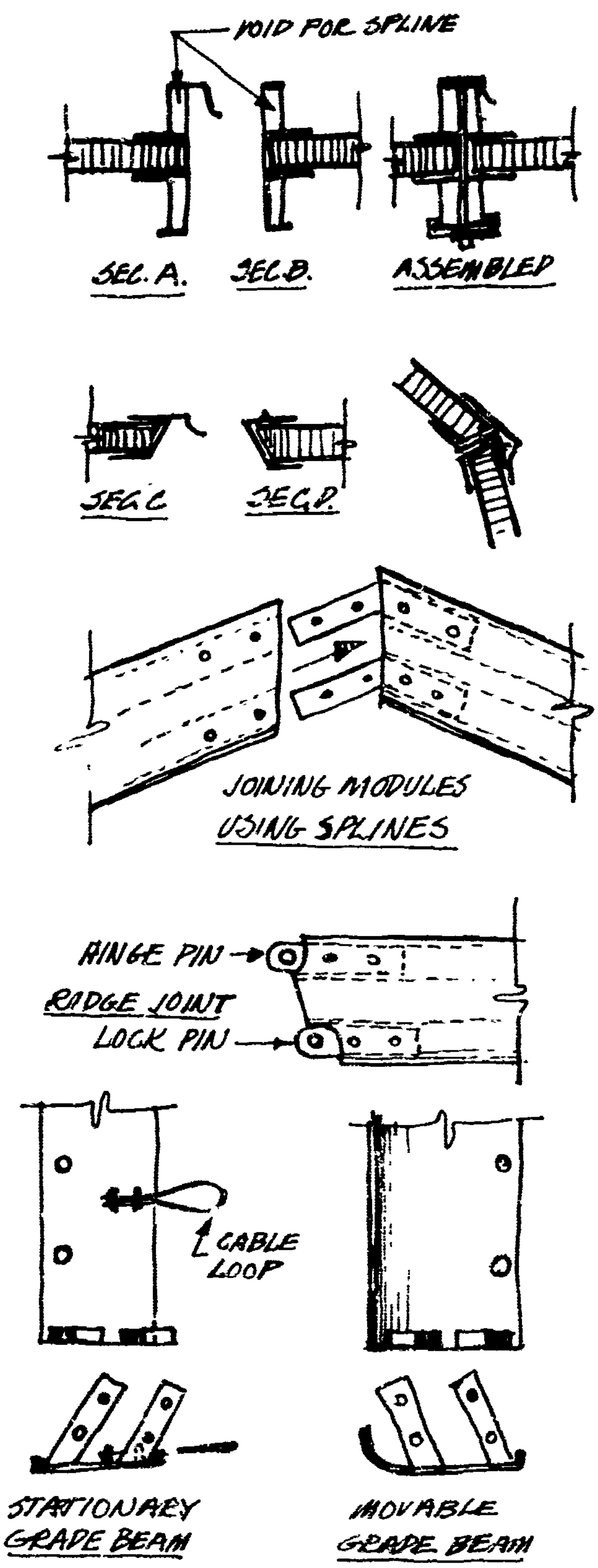
4.) Details

The sides of the panels would be set in metal edges which would be formed to interlock with the edges of the adjoining panels. The interlocking edge would become a flashed standing seam or arch rib in its erected state.

The ends of the panels would have metal edge strips with spring type projecting flanges and lock ridges. The flanges and ridges would strap into place during erection and the spring flange would flash the joint in the erected shelter.

The large metal edge pieces would be equipped with splines or gussets for joining the modules together transversely.





STRUCTURAL MODULE CONSISTS OF WEATHERPROOF LIGHT WEIGHT OR HONEYCOMB PANEL WITH STRUCTURAL EXTRUSION ADHERED & SEALED ALONG LONG EDGES. EXTRUSION INCLUDES WEATHER FLASHING & VOIDS TO ACCEPT SPLINES USED IN JOINING MODULES TO MAKE ARCH SECTIONS. JOINT AT RIDGE OF ARCH VARIES AS SHOWN. SEC. C & D SHOW METAL FLASHING ELEMENTS APPLIED TO ENDS OF PANELS.

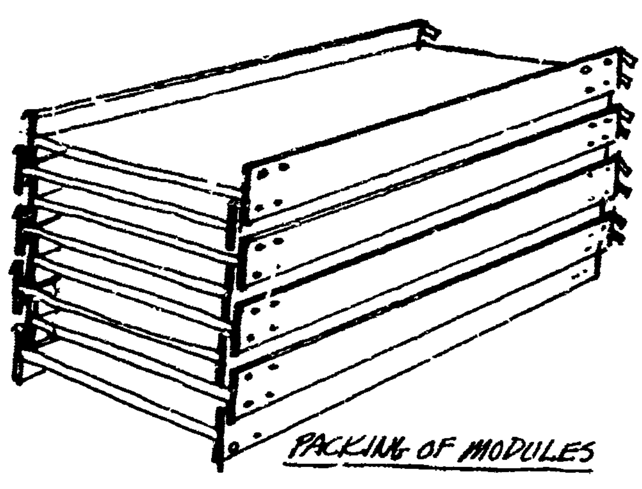


FIGURE 57. COMPOSITE PLATE WITH LINEAR ELEMENTS

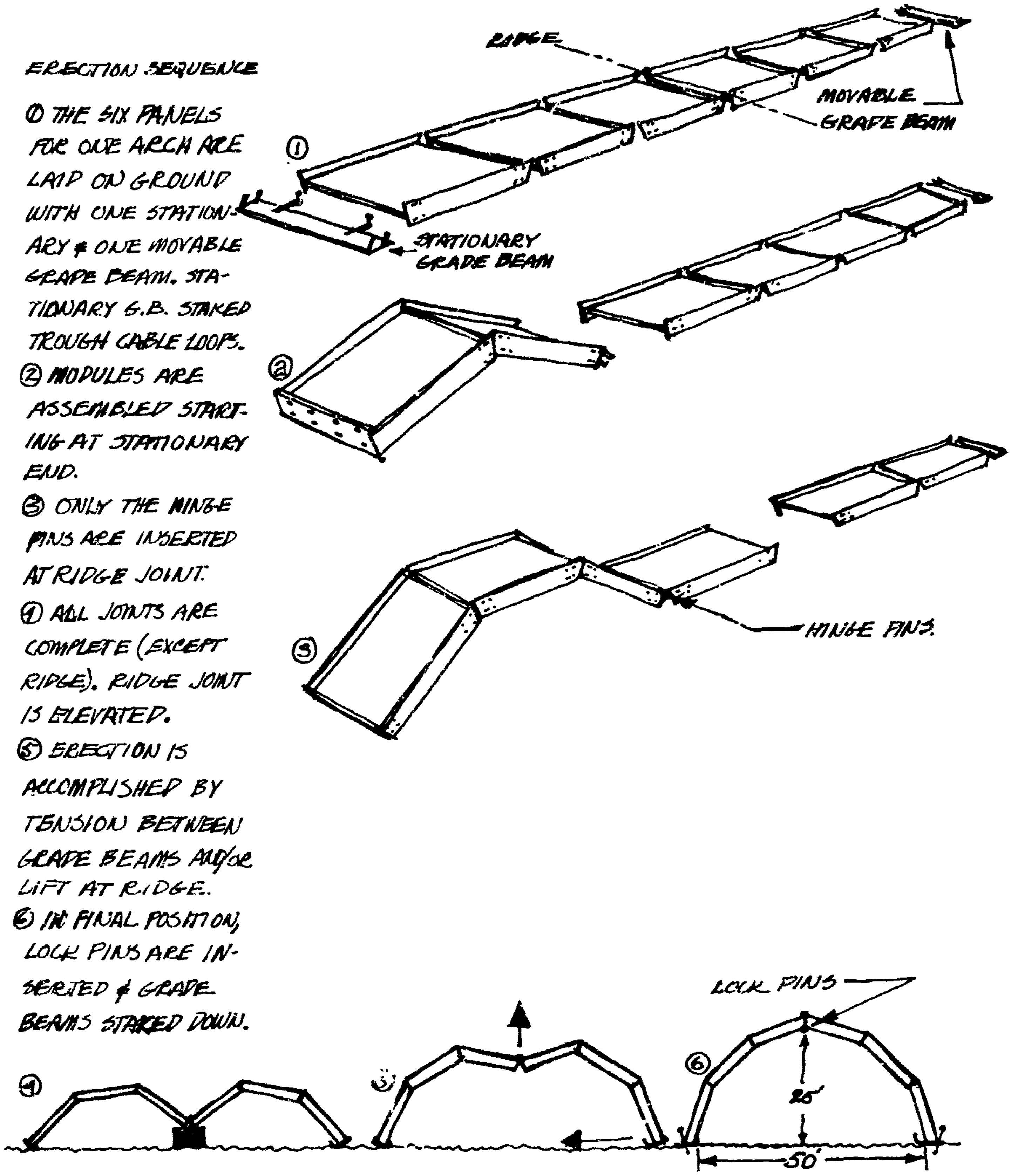
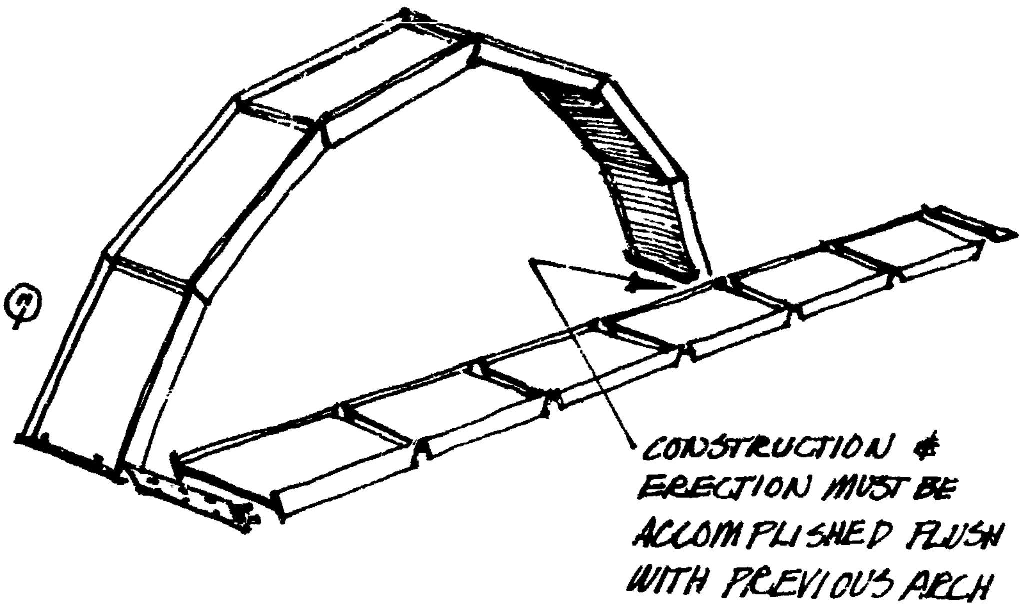


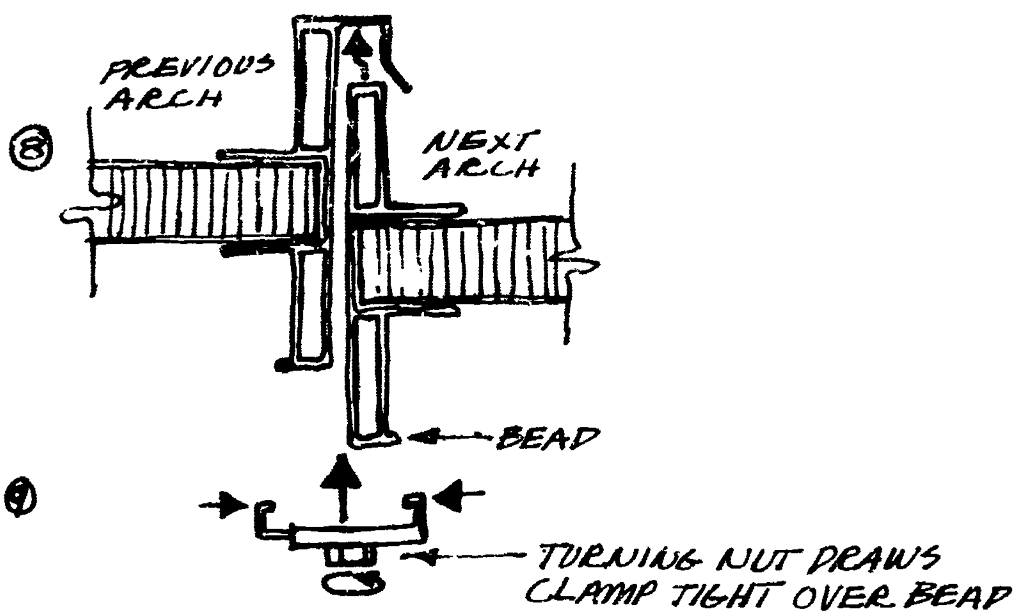
FIGURE 58. COMPOSITE PLATE WITH LINEAR ELEMENTS

⑦ STEPS ① THRU ⑥ ARE REPEATED TILL TOTAL LENGTH OF 80' IS ATTAINED

⑧ WHEN AN ARCH IS RAISED AGAINST PREVIOUS ARCH, EXTRUDED BEAMS NEST USING FLASHING AS GUIDE.

⑨ WHEN ARCHES ARE FULLY NESTED, CLAMPS ARE REMOTELY APPLIED TO LOWER EDGE OF BEAMS TO SECURE ARCH TO ARCH.





COMPLETED 50'x80' x25' HIGH HANGAR IS SHOWN WITH SIMPLE FABRIC ENDS.

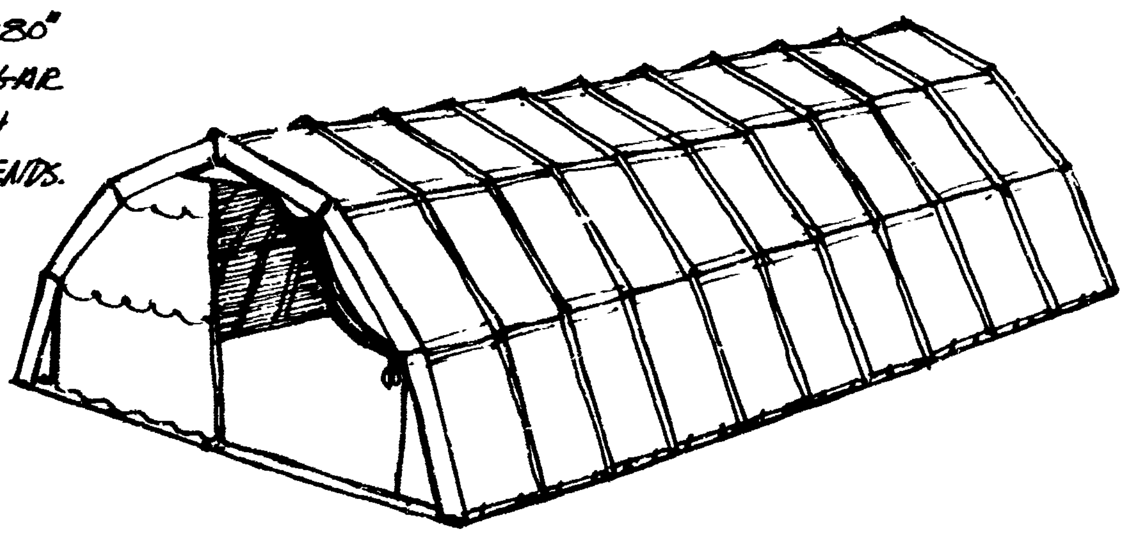


FIGURE 59. COMPOSITE PLATE WITH LINEAR ELEMENTS

5.) Packaging, Shipping, and Erection

The modules would be stacked flat, with the metal edges (ribs) staggered to reduce stack height. The stacks would be strapped to pallets for shipping.

Three modules would be connected to form a half arch. Two half arches would be pinned together at the hinge-pin of the apex or ridge joint. The apex joint would be jacked up slightly then raised to final position by applying tension to the cables with winches.

When the arch has been raised to its final position, lock pins would be driven through the apex or ridge joint splines.

The grade beams would be anchored to the ground and the tension cables could be removed if the splines or gussets were capable of sustaining all stresses, or the cables could remain to take the outward thrusts.

Adjoining arches would be locked together with special "Simmons" cam type connectors designed by this team for use on the small shelters in Section III.

6.) Summary

A simple study-model of a half arch was built but was not subjected to any special tests. No weight, erection time, or cost estimates were made.

The number of modules was reduced from other concepts. The insulated panel proposed in this concept eliminated the need to package and install insulation as a separate item as would be necessary in some other concepts, however the weight of this structure would be greater because of this same fact.

L. CONCLUDING STATEMENT ON HANGAR CONCEPTS

Comparisons of the good and poor qualities of the hangar design concepts and the estimates of weight, erection time, costs, etc., at this stage of the design research are purely academic.

Only through the construction of larger models, tests of these, then full size mock-ups and again tests, can calculations and estimates be given any sense of reality. The properties of materials seen and tested in small amounts, or combined with other materials in theory only, frequently change when applied to full size and large actual structures which are subjected to many unanticipated conditions.

Any of the hangar design concepts are feasible but the successful accomplishment of the goals set up for the project are not realistically predictable. The proof of these concepts could be had only by carrying the more promising ones through the development stages mentioned above before a full size hangar is built, as was done in the development of the essentially successful small shelter.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1.) Concurrence with provisions of contract

Concepts established for lightweight expandable structures followed the program for investigation outlined in the Statement of Work. One deviation, resulting from consultation with Headquarters TAC and concurred in by the Project Engineer, consisted of a change of square foot areas for Small Shelters from 175 sq ft and 300 sq ft to 512 sq ft (16' x 32'). It should be noted that the modular nature of the concepts developed would permit indefinite decrease below or increase above this area in increments of approximately thirty-two sq ft each.

The other deviation, again resulting from consultation with Hq TAC and concurred in by the Project Engineer, changed the type aircraft to be housed in the large shelter from an L-28 (Cessna type) to an F-4-B fighter aircraft. To accommodate this type aircraft, a shelter size of 50' x 80' (4000 sq ft area) was established.

2.) General conclusions on Small Shelter Concepts

a) A valid area for significant design exists between the category of fabric tentage on one hand and heavier rigid buildings of conventional materials requiring permanent footings on the other hand.

b) In order to keep down cubage, total weight, and package size, it is just as important to give as careful attention to design of packaging techniques and accessory items (floor coverings, doors, mechanical equipment) as to the shelter proper.

c) As in any modular or expandable structure, the method of connection of components is of vital importance. The design of the fastening system oftentimes holds the key to satisfactory performance in the areas of weather-tightness, structural unity, total package weight, and man hours consumed in the erection process.

d) While it may be relatively simple to design a satisfactory structure in a laboratory situation, the real validity of the design is largely determined by how it performs in the environment in which it is to be used (i.e., (1) A lightweight shelter is only as good as the anchorage to the terrain that can be provided. (2) A system of connectors must, on one hand, be positive enough to provide weathertight seals but, on the other hand, must have enough flexibility and/or tolerances to accommodate the inevitably encountered minor variations in terrain surface).

e) Simplicity of erection process is vital in recognition of the likelihood that, in use, the shelter will be erected by untrained personnel who are not familiar with the intricacies of a complex system.

f) As well as meeting the needs of the Air Force in the limited war situations outlined, expandable structures of the types being developed under this contract have a real potential use in such areas as (1) Civil Defense, and disaster relief applications (2) use in underdeveloped nations (3) migrant worker temporary housing, and (4) recreational uses.

3.) General Conclusions on Large Shelter Concepts

The design concept studies for the hangars have not been carried far enough to indicate that any of them would absolutely result in satisfactory full size structures. However, the proposals at the stage of development required under this contract have sufficient feasibility to warrant further studies and development of at least some of the concepts.

4.) Specific Conclusions on Small Shelters #1 and #2

a) Concurrence with provisions of Amendment to Contract

Two shelters were constructed in accordance with the requirements of the Statement of Work. They have been described in this report as "Small Shelter #1" and "Small Shelter #2". Field testing has been accomplished. The field tests did not produce winds of over 45 knots for Small Shelter #1 or 30 knots for Small Shelter #2. However, the contractor is confident that the shelters will sustain 55 MPH winds. A tropical test of Small Shelter #2 now being conducted under another contract should give more specific data as to the vermin and fungus-proof qualities of the materials used.

b) Specific Conclusions on Small Shelter #1

As summarized in Section IID of this report, Small Shelter #1 performed very satisfactorily from a structural standpoint. The erection technique was simple and could be comprehended by relatively untrained personnel. The basic Fome-Cor material and the Aroflint 505 finish was both satisfactory from a functional standpoint. The only functional deficiency noted was inadequate sealing at joints that permitted considerable leakage of rain water.

c) Specific Conclusions on Small Shelter #2

Areas in which improvement was sought in the design and construction of Small Shelter #2 (as compared with Small Shelter #1) were (1) more effective sealing against leakage, (2) reduction of grade beam weight, (3) reduction of number of component parts, (4) reduction of erection time, and (5) lower gloss exterior finish.

All of these objectives were achieved in Small Shelter #2. The adoption of Velcro nylon fasteners expedited erection and eliminated easily lost separate detached connector devices. Aluminum grade beam, as well as reducing weight, grounded the main structural components of the shelter packages. After six erections in five different geographic locations, no material deterioration has developed and accidental damage or bruising is minimal and in no way critical.

B. RECOMMENDATIONS

1.) For Small Shelters

a) Explore possibility of manufacture of a wall material with liners of a material that integrally posses the following characteristics: (1) integral color with low gloss or matt finish, (2) high resistance to puncture or tear, (3) water and weather resistance, (4) vermin and insect repellant surface, (5) fungus and rot resistant surface, and (6) capability for scoring and folding without cracking. These characteristics, to the degree possible, are now obtained by application of coatings to the Kraft paper lining of the "off-the-shelf" Fome-Cor foamboard material.

b) Further analysis of the validity of variations in design to accommodate different climatic situations. If this is desirable (i.e., ends that are open but screened for maximum ventilation in tropical use), it is recommended that such components be designed so they require no change to the basic design of the structure, but can merely be substituted as units as required by the climatic situation to be encountered.

c) Further investigation into the need of designing interior partitions and transitional connecting sections so as to make possible (1) division of interior of shelter and (2) creation of shelters with floor plans of more complex form than the basic rectangle (i.e., "L", "T", or "X" plans.)

d) Further investigation into lightweight panelized floor systems (possibly supported above ground) for applications in which the plastic tarpaulin floor is not considered satisfactory.

e) Further study and testing of Velcro fastenings to eliminate any possible "over designing" of connector strength with the objective of possibly reducing quantities, sizes, and costs of this item in the shelter.

f) Further field and use tests of Small Shelter #2 to point up (1) any functional or operational improvements that such field use might reveal and (2) any possible reduction of weight and quantities of materials required.

2.) For Large shelter

a) More detailed engineering study of the more promising concepts developed under this contract.

b) Building and testing of a typical section (or arch) of the most promising design.

c) Construction of a full-size 50' x 80' prototype large shelter.

VI. REFERENCES

Modern Plastics Encyclopedia, Breskin Publications, 1965

Kaswell Handbook of Industrial Textiles, Wellington Sears, 1963.

"Textile Fibers and Their Properties," Burlington Industries, 1963.

Laughner and Hargan, Handbook of Fastening and Joining of Metal Parts, McGraw-Hill, 1956.

Blickensderfer, "A Primer of Wind Loads on Gable Roof and Flat Roof Buildings," Metal Buildings Manufacturers Association.

Paraskevopoulos, Borkin, Darvas, Larson, "The Potential Use of Foam Plastics for Housing in Under-developed Areas," University of Michigan, 1965.

Bulletins of Paper Honeycomb Materials, Forest Products Laboratory of U.S. Department of Agriculture Forest Service.

Technical Reports on various materials and structures, Air Force RTD, WPAFB, Dayton, Ohio.

SATS Equipment Catalog, Ship Installations Office, Bureau of Naval Weapons, Department of Navy, 1965.

Technical Reports on Tests of Various Buildings; Project NY 500-002-2,3,14,15,16,20,22,31,33,35,36,37; and Projects 135, R,176, R,234; U.S. Naval Civil Engineering Laboratory, Port Hueneme, California.

Bulletins and Technical Reports, Fome-Cor, Springfield, Mass.

Salvadori and Heller, Structure in Architecture, Prentice-Hall, 1964.

Weidlinger, Aluminum in Modern Architecture, Vol. I and II, Reynolds Metal Co., 1956.

Various Expandable Type Structures, including:

Hangars by Walter Kidde Company, Ltd., Middlesex, England.

Geodesic Structures by Synergetics, Inc., Raleigh, N. C. and Pease Woodworking Company, Hamilton, Ohio

Structuresby Birdair Structures, Inc., Buffalo, N. Y.

Techbuilt Steel Houses by Armco Steel Corp., Middletown, Ohio.

Structures of Polyurethane Foam by Raven Industries, Inc.
Sioux Falls, S. D.

Fiberboard Structures by Outdoor Fibre Products, Inc.,
Chelsea, Michigan.
and Mead Paper Co., Chillicothe, O.
and Monsanto Corp., St. Louis, Mo.

Marine Corps Experimental Hangar, Lakehurst, N. J.

Magnesium and Aluminum Structures by Magline Corp.,
Pinconning, Michigan.

Hangars by Brooks and Perkins, Detroit, Michigan.

Shelters by Royalite Porta-Buildings, U. S. Rubber Company,
Mishawaka, Indiana.

Numerous magazine articles and illustrations.

Numerous manufacturers' catalogs, technical brochures, and
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13. ABSTRACT

Lightweight expandable shelters for limited war applications are described.

Concepts for both small (16 ft wide) and large (50 ft wide) shelters are presented.

Included in the small shelter section is the development of several different geometric configurations and methods of assembly. The construction, testing, and erection of prototype shelters based on two of the concepts are covered. Both shelters described utilize plastic foamboard as the basic construction material. Data on static load tests, erection time, package cubage, and package weight are included.

Several structural concepts for the large shelter are presented. This structure, designed to serve as a hangar for a fighter aircraft, is carried through the concept stage only. The various concepts are described and sketches illustrating their key features are presented.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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