SESSION II

LIGHTWEIGHT, EXPANDABLE SUPPORT SHELTER SYSTEMS

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BACKGROUND

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.

INTRODUCTION

Under the sponsorship of the Support Techniques Branch, Aero Propulsion Laboratory, Wright-Patterson Air Force Base, a group of researchers at the University of Cincinnati is engaged in a program seeking to establish new and unique design concepts for lightweight expandable shelters to be utilized in limited warfare actions. (Contract # AF 33 (615) 1285)

The members of the group are, from the Department of Industrial Design: Professors James M. Alexander (principal project leader) and Joseph M. Ballay and, from the Department of Architecture: Professors Karl H. Merkel (associate project leader), Bruce E. Goetzman, and Richard H. Stevens. A full-time research assistant, Lawrence Fabbro (Industrial Design 1964), and several upper class co-op students have also participated.

The work under the contract was to develop concepts for two types of structures: (1) small general purpose shelters and (2) large (50' span) shelters capable of housing fighter aircraft.

The work has progressed along the following lines:

1. further definition of problem
2. concept studies on both large and small shelters
3. construction and testing of full-size small shelter # 1 (under amendment to the contract)
4. further studies of small shelter concepts
5. construction and testing of full-size small shelter # 2 (under amendment to the contract)
6. resumption of concept studies for large shelter (stage of work at time of writing of this paper).

This paper will follow the above outline except that all discussion of studies for the large shelter shall be deferred to the end of the paper.

DEFINITION OF PROBLEM

To further determine the detailed needs of the Air Force, trips were made to Eglin Air Force Base, Florida and Langley Field, Virginia. Conferences at Eglin acquainted the group members with capabilities of transport aircraft, extraction techniques, and needs for low-cost - possibly disposable - shelters in limited warfare situations.

At Headquarters, Tactical Air Command, Langley Air Force Base briefing on Bare Base operations and use of the Gray Eagle package was held. It was recommended that the small shelter should fill an existing gap between (1) existing tentage and (2) panelized prefabricated structures of conventional materials. Design criteria established that the shelter (1) should be designed for approximately five erection and disassembly cycles, (2) should, with moderate maintenance, have a useful erected life of up to two years, (3) should withstand winds of 50 knots, (4) should support a live load of 5 to 8 pounds per square foot, and (5) should be capable of being insulated.

An inside width of sixteen feet was considered optimal and the structure should be capable of being expanded in length. Lightness of weight, low package volume, short erection time, and simplicity of erection process were major design goals.

The large shelter has as its design objectives: (1) size: approximately 50'x80'x25' high, (2) live load: 20 PSF, (3) wind load: 80 mph, (4) temperature range -25° to +125°f., (5) as low total weight, package cubage, and erection time as possible.

SMALL SHELTER CONCEPTS

INITIAL CONCEPTS

Initially considered concepts included air-inflated or air-supported structures and structures employing foamed in place structural elements. The former were not pursued largely because of duplicate efforts by other services and the latter was not followed because of the still-developing state of the art in this sophisticated concept.

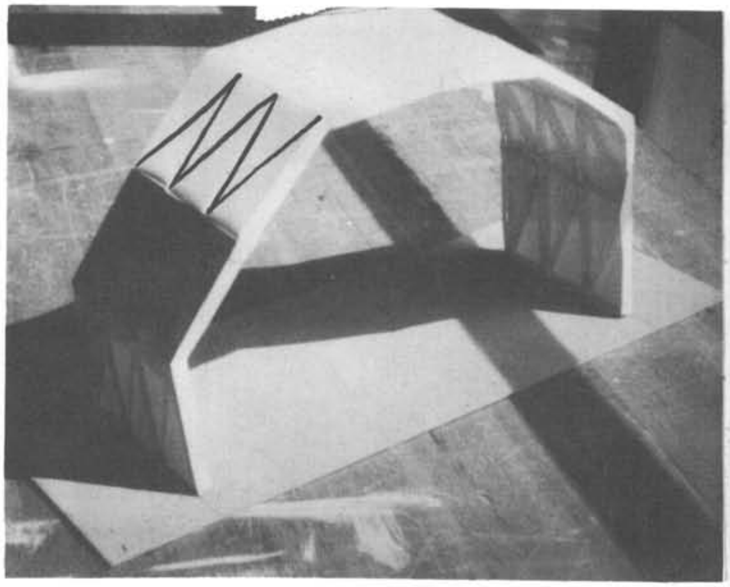


FIGURE 1. Scale Model - "bow-tie" concept.

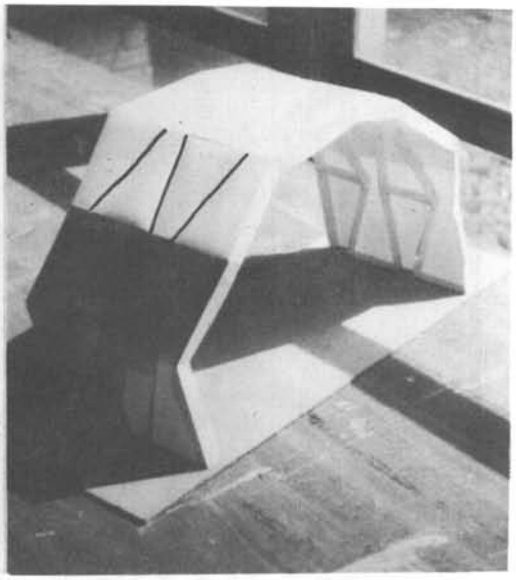


FIGURE 2. Scale Model - modified "bow-tie" concept.

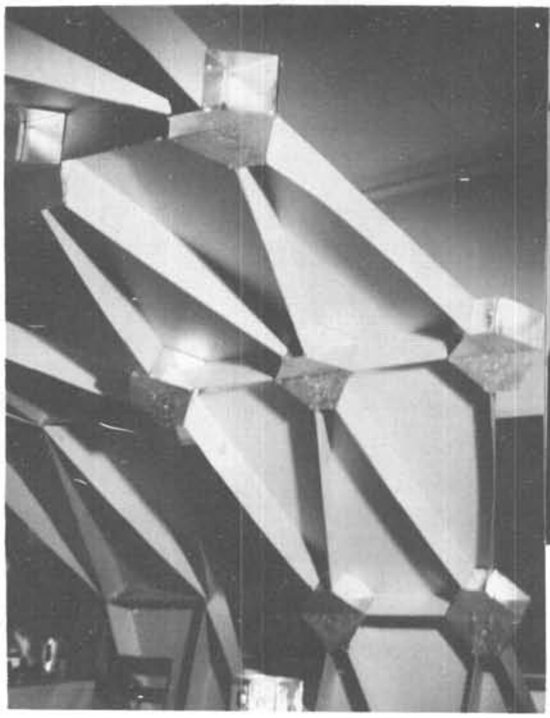
The general area of modular panelized concepts utilizing inexpensive light-weight sheet material was settled on.

"BOW-TIE" MODULAR CONCEPT

Preliminary studies of various geometric configurations led to a "bow-tie" shaped module (Figure 1) that seemed to offer great rigidity through ribs formed by turning down the edges of the modules. A variation (Figure 2) suggested a reduction of number of modules required but gave less rigidity because of the lack of continuity of the diagonal ribs.

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.
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



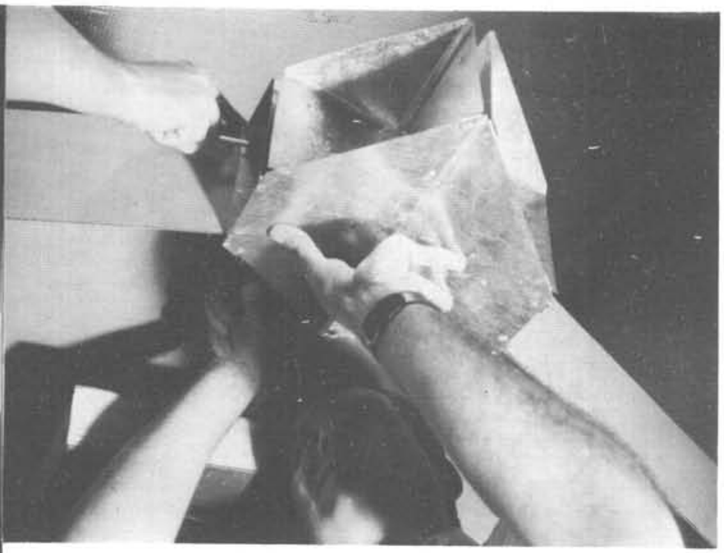


FIGURE 4. Detail - "Asterisk" connector being installed on full-size test arch.

FIGURE 3. Test arches of corrugated fiberboard. "Bow-ties" attached by (left) cherry rivets and (right) sheetmetal "asterisk" connectors.

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 easy reshipment.

<u>Test arch using cherry rivet connectors</u>

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 the left arch in Figure 3.

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.

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.

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-pealing of joints was deferred until this structural feasibility was established.

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 on the right in Figure 3, and the connector is shown being installed in Figure 4.

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.

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 ¼ inch and 3/8 inch.

For this arch 3/8" thick Techni-Foam was used. The folded ribs of the "bow-tie" modules were reinforced with 28 ga. galvanized iron strips having a "J" section (2"x3/8"x5½"). The connectors used were Simmons spring-loaded type #W7. The assembled test arch is shown in Figure 5, and the Simmons connector is shown in Figure 6.

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.

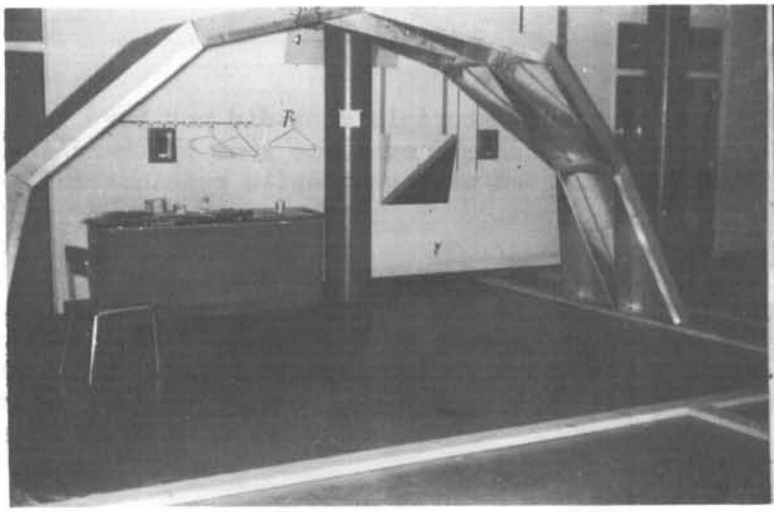


FIGURE 5. Test arch - TECHNI-FOAM with sheet-metal reinforcement and SIMMONS connectors.

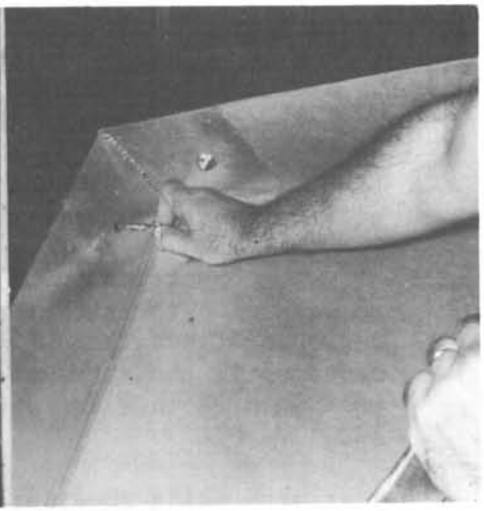
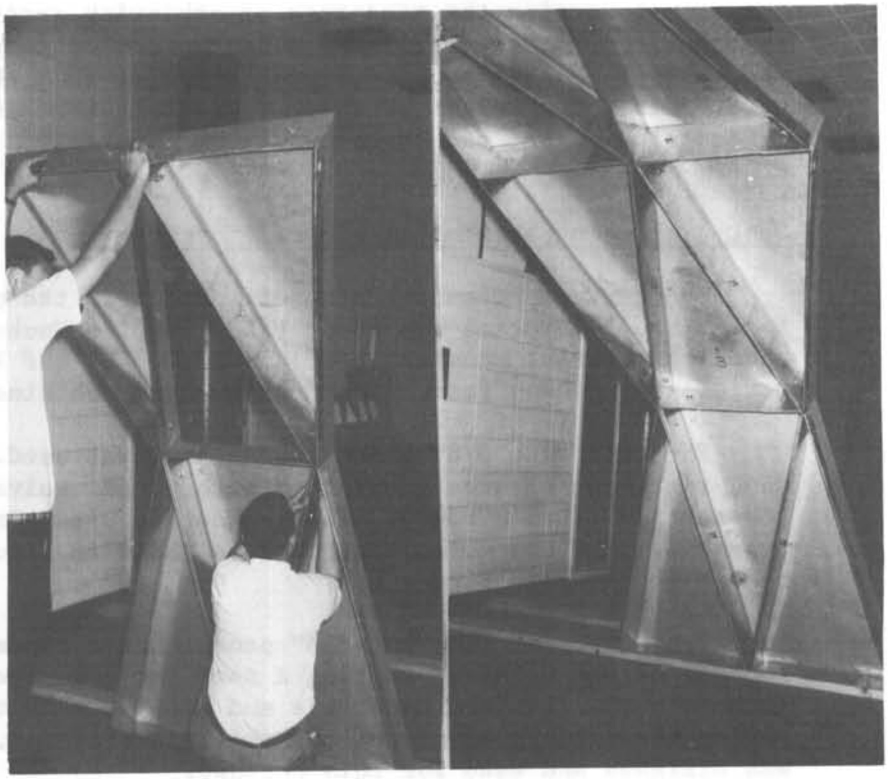


FIGURE 6. Detail - SIMMONS connector.

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.



FIGURES 7 and 8. Construction of test arch shown in Figure 5.

FIGURE 9.
Test Arches - Fome-Cor (left), Techni-Foam (right) with minimal sheetmetal reinforcement and thumbscrew/wingnut connectors.

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"x¼"x1" 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"x1" steel strap stirrup with washers and thumbscrew was designed to secure the waist of the module in its folded position. 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 showed the following:

	1/4" Techni-Foam	1/4" Fome-Cor
1. weight per sq. ft.	.202 lb.	.155 lb.
2. adhesion liner to foam	-	superior
3. surface smoothness	-	superior
4. resistance to chemical action.	superior	-
5. resistance to intense heat	superior	(melted at 180°f)
6. resistance to indenting	superior	-

To secure comparative structural data identical "bow-tie" modules and test arches were constructed and subjected to static load tests. Test arches in Fome-Cor and in Techni-Foam are shown in Figure 9.

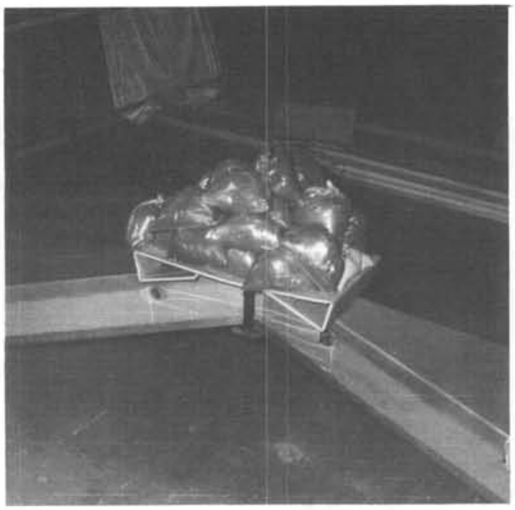


FIGURE 10. Concentrated load test - "bow-tie" module.

FIGURE 11. Concentrated load test - inverted "bow-tie" module.

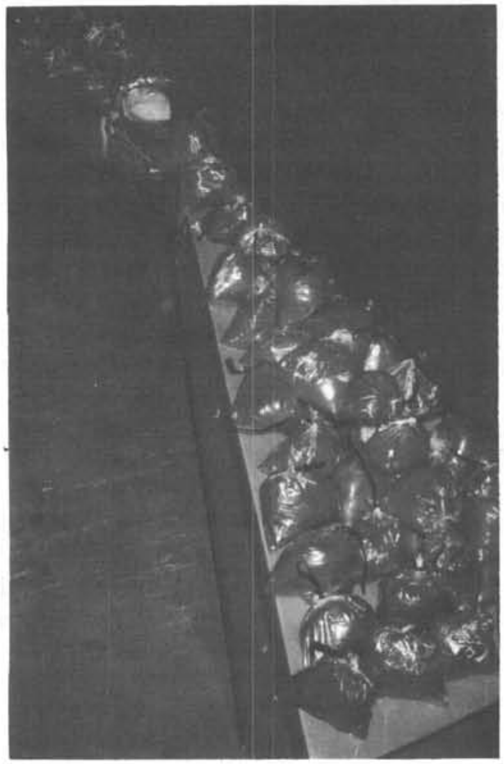


FIGURE 12. Uniform load test on Arch shown in Figure 9.

FIGURE 13. Uniform load test - "bow-tie" module

Tests on individual "bow-tie" modules produced the following data. Reinforcement in line with changes outlined on preceding page was found most effective in this series of tests.

Type of test	Figure #	Techni-Foam module	Fome-Cor module
1. Center load, module upright	10	Failure at 44 #	Failure at 60#
2. Center load, module inverted	11	Not tested	No failure 60#*
3. Uniformly distributed load (8½ sq.ft.)	12	No failure at 100#*	Failure at 160#

* not tested to destruction

Two complete modular arches (one using Techni-Foam, one using Fome-Cor) were tested by the application of gradually increasing uniformly distributed loads as shown in Figure 13. Failure occured in the Techni-Foam arch as the load approached 10 lb./sq.ft. and in the Fome-Cor arch as the load approached 8 lb./sq.ft. Vertical deflection on the Techni-Foam arch was 1-13/16" at the ridge at 8 lb./sq.ft. load. On the Fome-Cor arch it was 1-13/16" at the ridge at 6 lb./sq.ft. load. It was felt that the testing of just one arch rather than a completed structure was an unfair test. (Note: Construction of Shelter #1 proved that this was true.)

CONSTRUCTION OF SHELTER # 1.

At the conclusion of the structural tests described above, the research group (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.

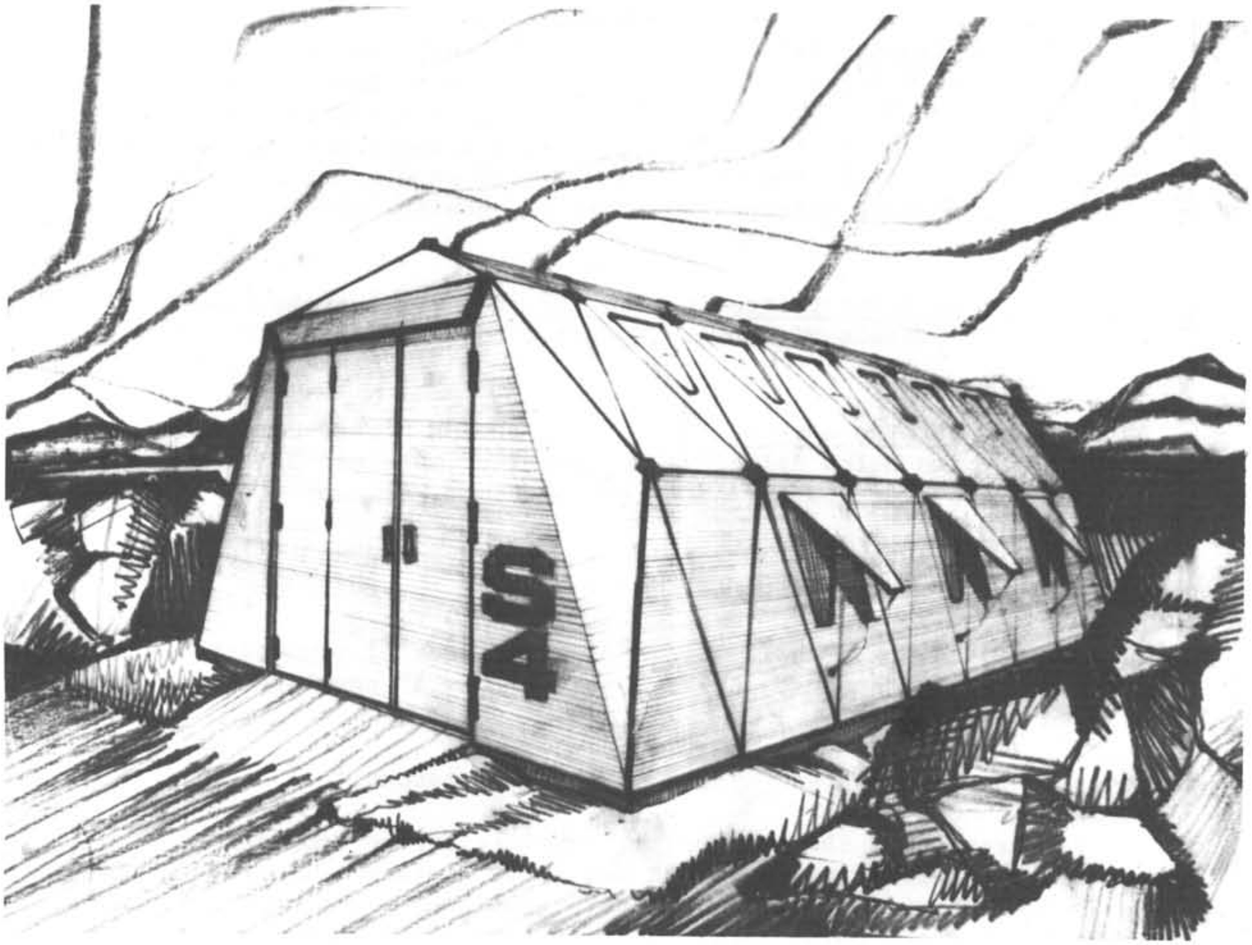


FIGURE 14. Rendering-Shelter using "bow-tie" concept.

Dimensions specified for Shelter # 1 were 38' long x 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. It was delivered for field testing on 1 September. 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'x6'-10" opening, door material: 1½" thick Urecomb (Union Bag-Camp Paper), door frame: wood head and jambs (shipped K.D.). (b) three interchangeable units to fit within 8'x6'-10" opening: single 2'-10" x 6'-10" x 1½" thick Urecomb 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 1¼" 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 cut outs in Fome-Cor, screened on inside, top hinged protective shutter, operating rod.

Grade beams: 4½" x 7" hollow wood sections made of plywood and 2 x 4's connected by 4 x 4 "tongues" locked into place by ½" 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, (3) thumbscrew/wingnut connector installation was time-consuming. Weight of the 16' x 38' shelter (less wood grade beams, stakes and tarpaulin) was 837 lbs. Figure 15 shows basic drawings and Figures 16, 17, and 18 views during production and test-erecting at the University.

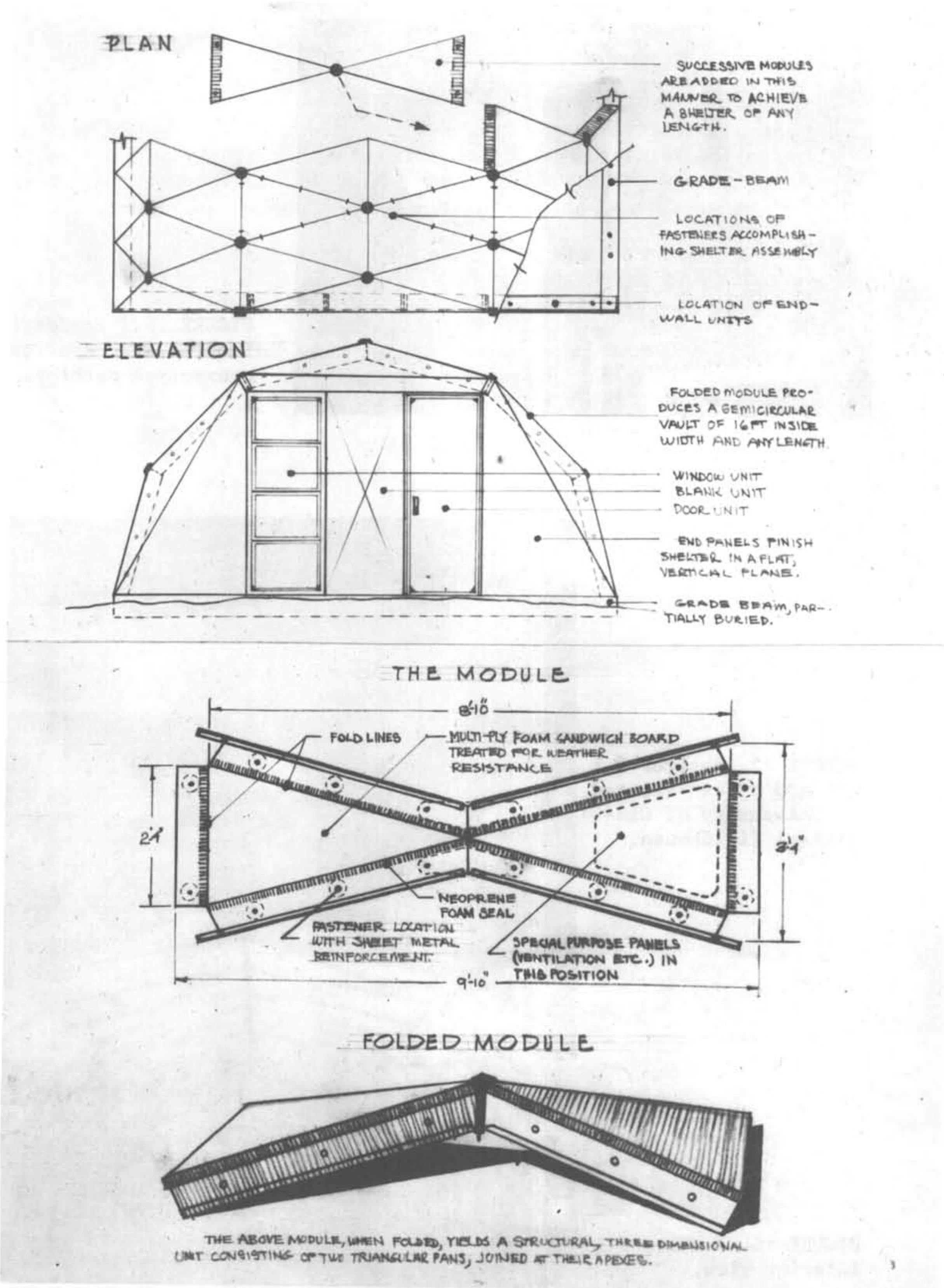


FIGURE 15. Plan, elevation, and module drawings, "bow-tie" concept. Shelter # 1.

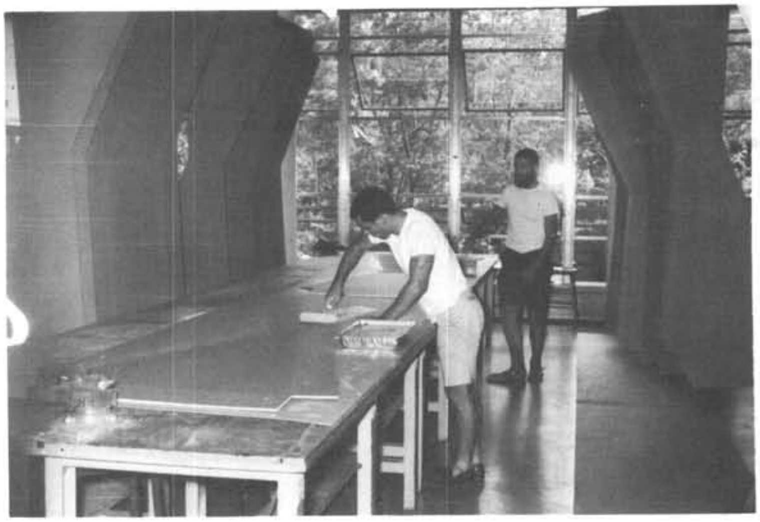


FIGURE 16. Production of Shelter #1. Application of epoxy-type coating.

FIGURE 17. Shelter # 1 (16'x38') test-erected in University of Cincinnati fieldhouse.

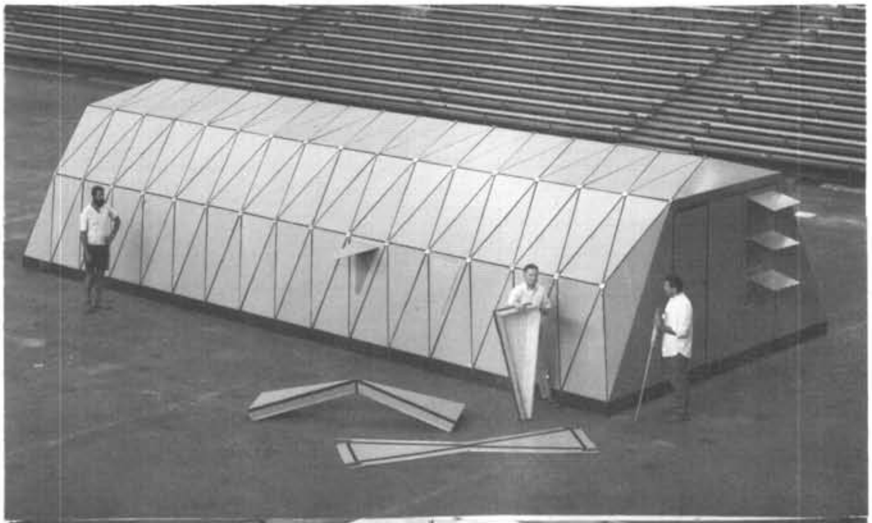


FIGURE 18. Shelter # 1 interior view.

FIGURE 19. Shelter #1 Field test-Indian River III exercise, Eglin Air Force Base, Fla. September, 1964

FIELD TESTING OF SHELTER #1

On 2 September, 1964 Shelter #1 was shipped by air to Eglin AF Base for erection, testing and use as a command post briefing room at Indian River III exercise. Erection was accomplished by a five-man University team in approximately five hours (25 man hours) in 103° f. temperature. Sixteen days later it was dismantled, repackaged, and air-lifted to Wright-Patterson AF Base and then returned by truck to the University of Cincinnati.

During the test the structure performed satisfactorily from a structural standpoint. At one time it withstood winds of approximately 45 mph with no significant vibration or deflection of components. Auxiliary tie down ropes and stakes provided for such contingencies were employed during this storm.

As anticipated, considerable leakage was encountered in heavy rain. Joints were taped, as an expedient, for the remainder of the test to assure its being waterproof.

FIGURE 20. Shelter #1 - Unpacking basic package.

FIGURE 21. Shelter #1 - Erection at Eglin AF Base, Florida

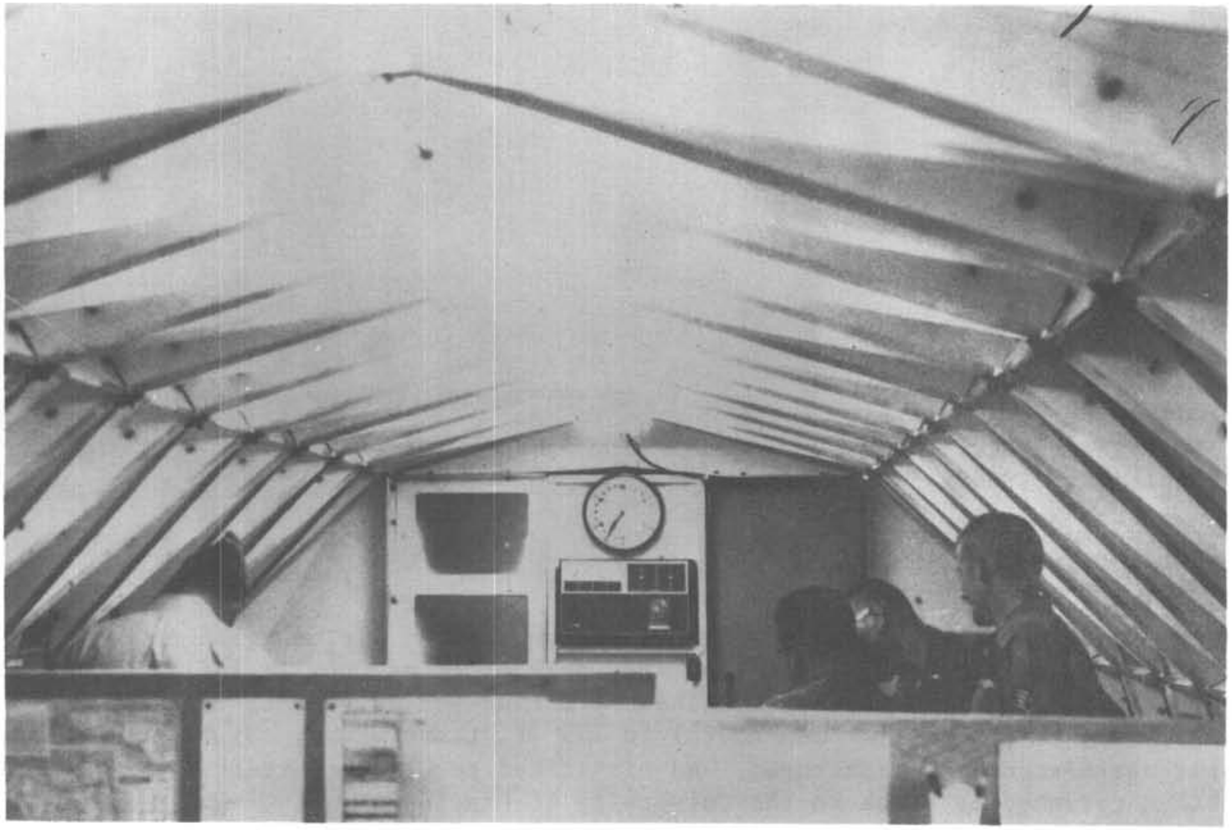


FIGURE 22. Shelter # 1 in use at Indian River III exercise.

For this exercise the Air Force at Eglin provided standard 4' x 8' plywood floor sections which fit within the 16' interior dimension between grade beams.

The surface coating of the modules proved satisfactory as did the foam sandwich material employed.

Design goals for further studies were: (1) more effective sealing against leakage, (2) reduction of weight by use of lighter weight grade beam, and (3) more rapid erection time by employing a less time-consuming connecting device that the thumbscrew/wingnut one.

FIGURE 23. Shelter # 1 interior view during erection.

FIGURE 24. Shelter #1 Snow-load test at University of Cincinnati. February, 1965

PROPOSED IMPROVEMENTS

After the return of Shelter #1 to the campus, a shortened 16'x20' section was erected and, to date, has stood in all kinds of weather for eight months (See Figure 24). No deterioration of material or finish can be detected.

Studies have been made in order to improve weather seal and reduce erection time by reducing time required to install connectors. Figure 25 shows the proposed change featuring continuous aluminum strips (to assure even pressure along length of joints) and an adaption of a Simmons cam-activated fastener.

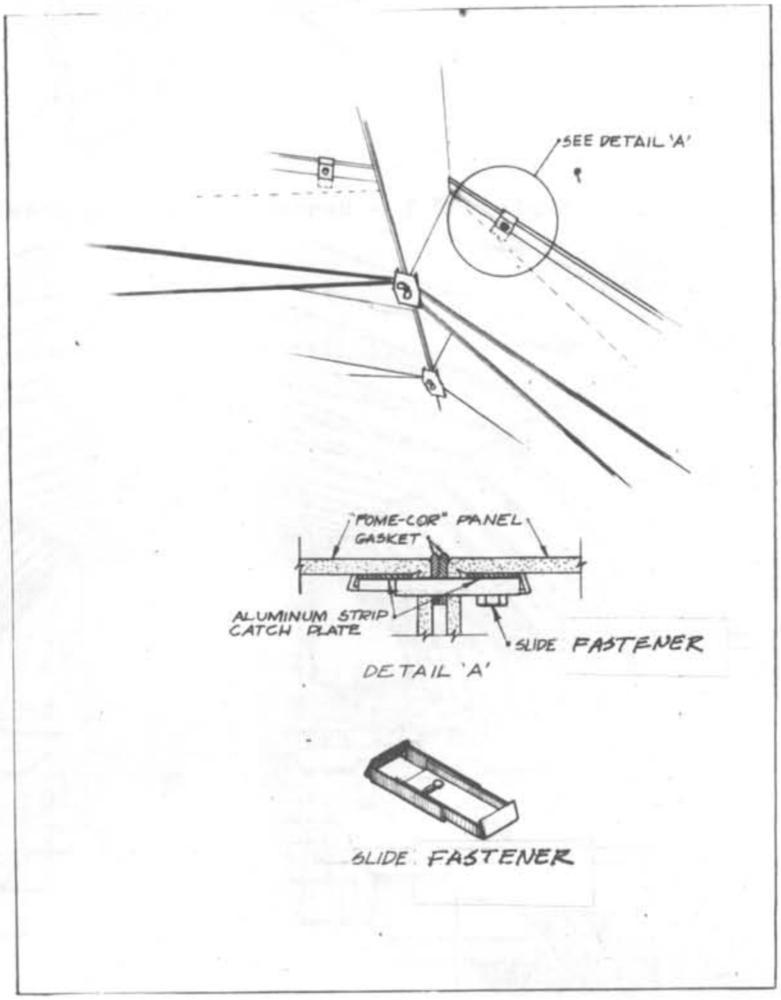


FIGURE 25. Shelter # 1. Proposed improved connector concept.

FIGURE 26. Shelter # 1 - Rendering showing possible use as a field kitchen.

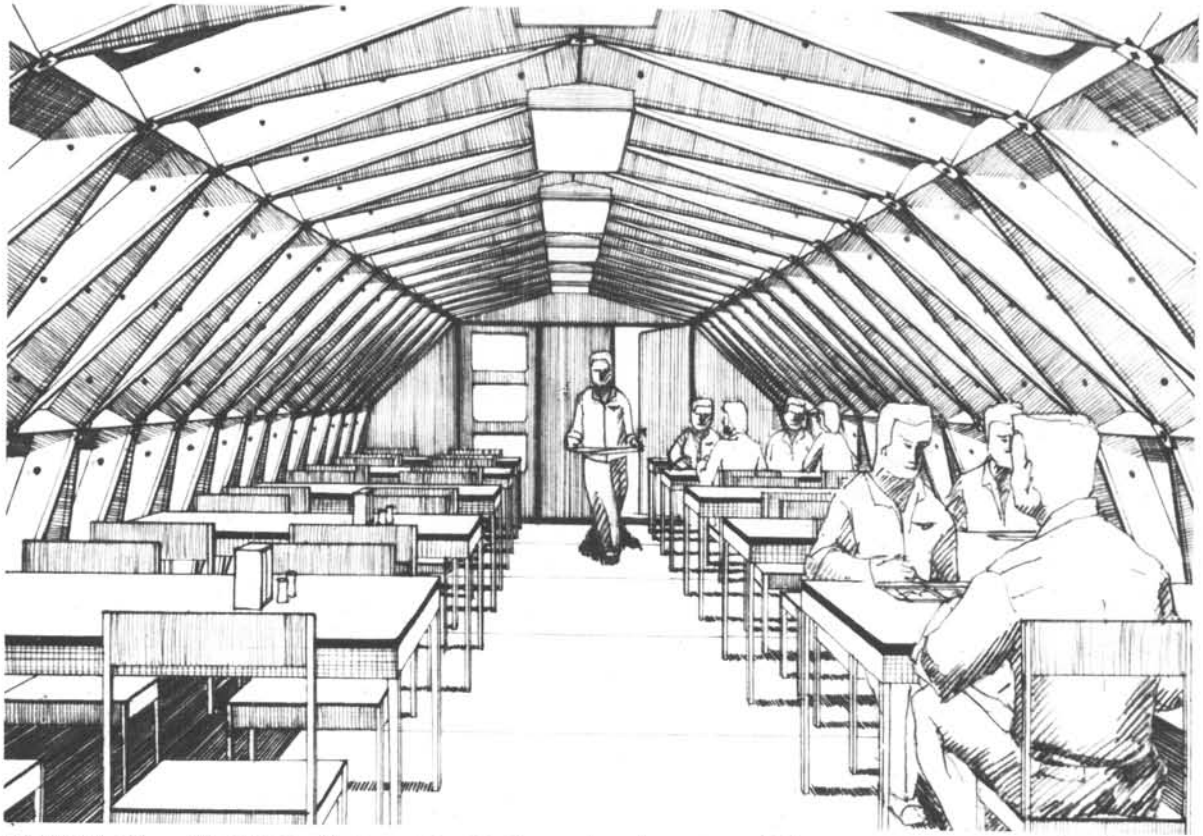


FIGURE 27. Shelter # 1 - Rendering showing possible use as a mess hall.

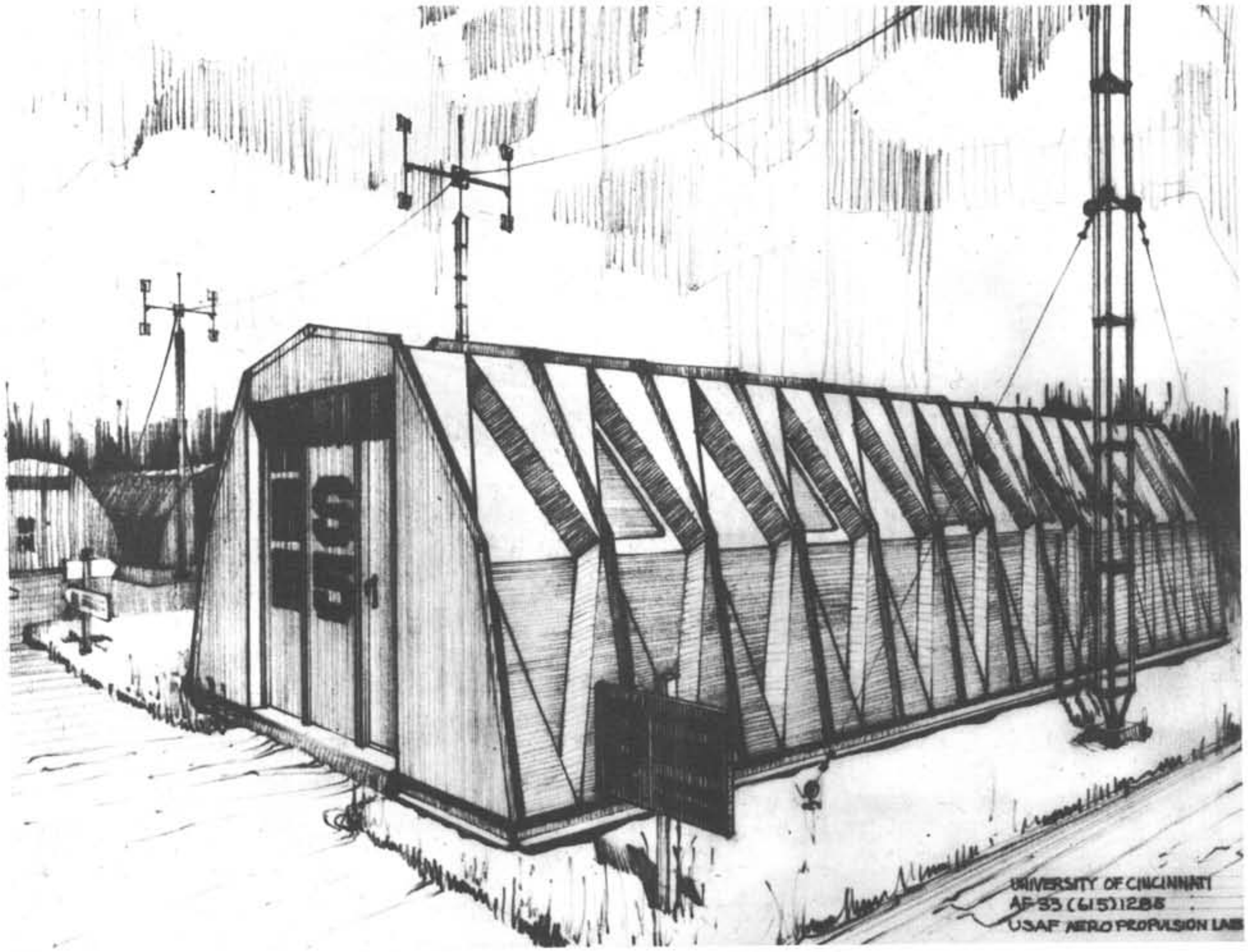


FIGURE 28. Rendering - Shelter using "folded-diamond" concept.

"FOLDED-DIAMOND" CONCEPT

Orders were placed for a number of specially fabricated modified Simmons slide fasteners (Figure 25) and certain gasket sections for adaptation to the "bow-tie" shelter. While delivery of these items was awaited, another concept was evolved.

This concept was based on a folded plate formed from a rectangular flat sheet of 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).

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.

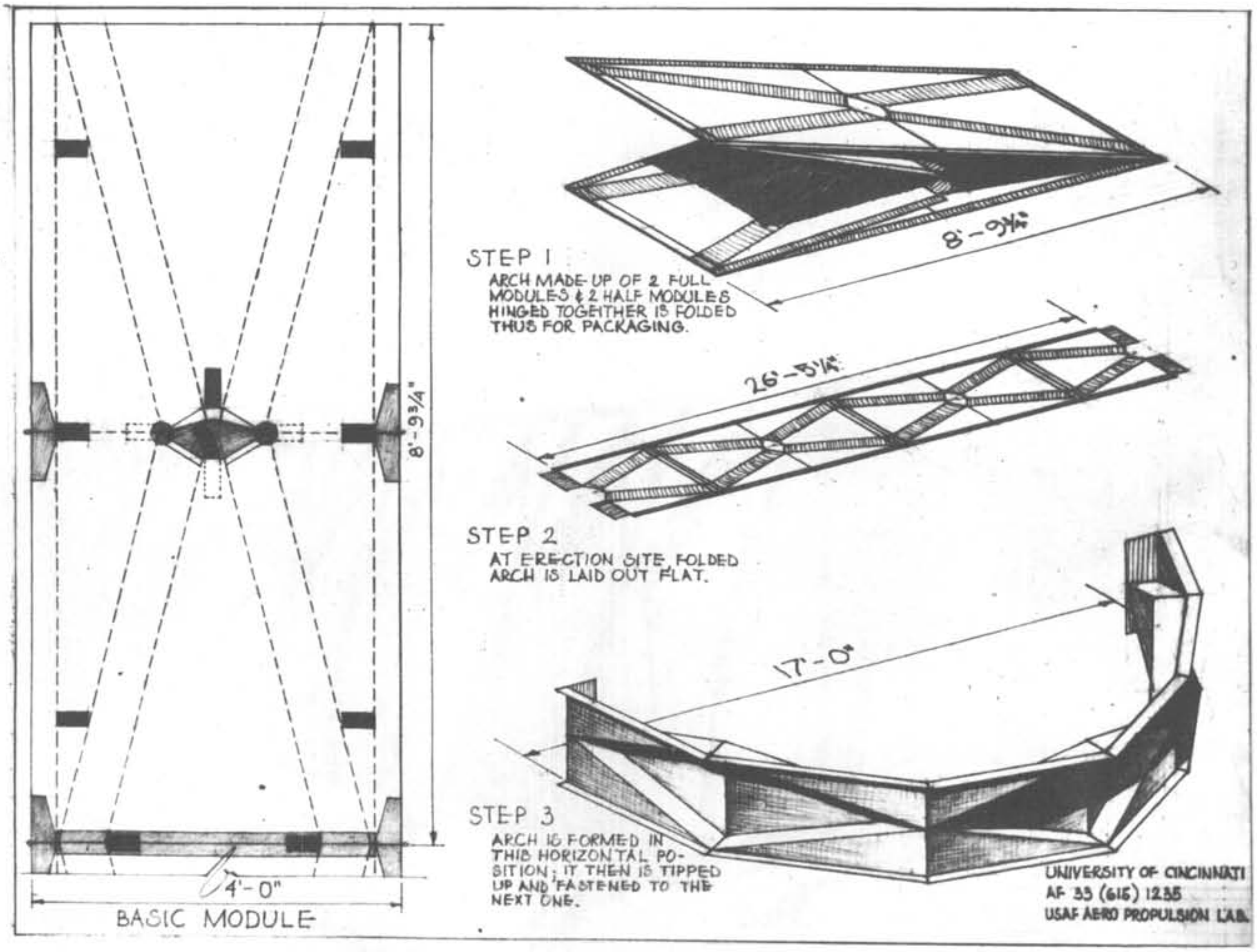


FIGURE 29. Drawing - Basic Module and Typical Arch-"folded diamond" concept.

A preliminary full-size triple arch in corrugated fiberboard was constructed to verify the basic geometry (See Figure 30). Figure 29 shows a further refinement involving stand-up ribs at joints, metal-reinforced and treated-fabric diaphragm-covered orifice 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 snuggly over the standing ribs.

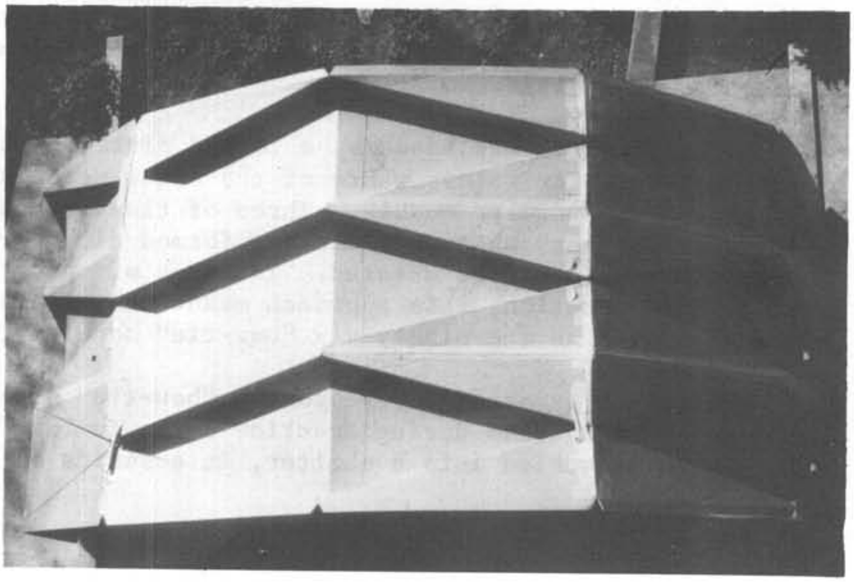


FIGURE 30. Test Arch in corrugated fiber board. "Folded diamond" concept view from above

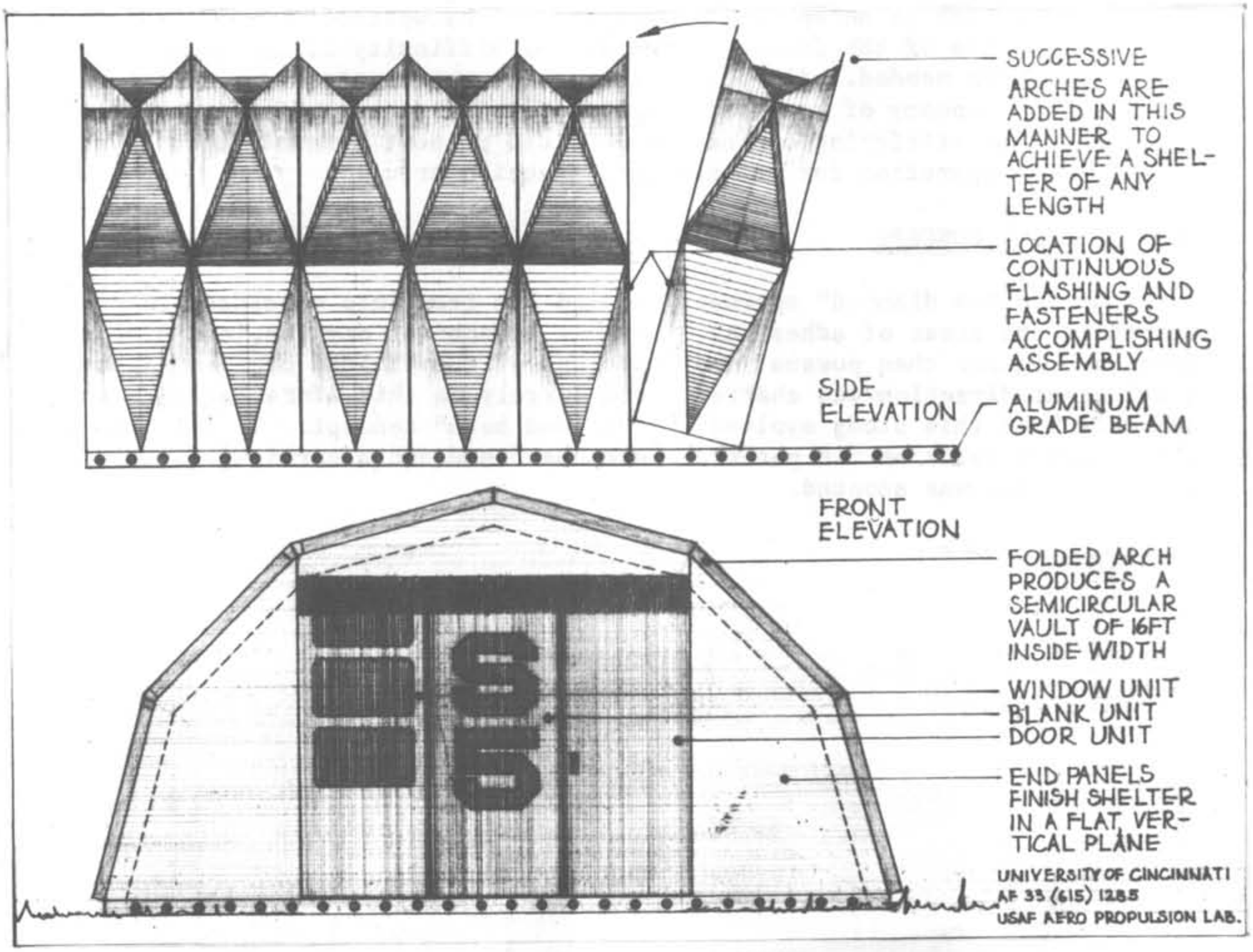


FIGURE 31. Drawing - Elevations of "folded diamond" concept shelter

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 light-weight aluminum grade beam was designed but was not available for this test. The test arch was loaded to 8 lbs. per square foot. Failure occured 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 occured when the upright ribs buckled at the first hinge point above the grade beam.

FIGURE 32. Test arch Fome-Cor "folded diamond" concept.

One drawback to an approach characterized by upstanding ribs and the alternating planes of the folded prisms is the difficulty of applying additional insulation when needed. Although this concept represented a step forward in the areas of economy of material and reduction of numbers of components, it needed further stiffening of the ribs and did present a fairly complex on-the-site folding operation for an untrained erection crew.

"FOLDED BEAM" CONCEPT

The "folded diamond" approach had led the team into considerable research in the areas of adhesives, flexible attachment devices, and coated fabrics. Rather than pursue modifications of the "folded diamond" approach a different direction was charted based largely on this aforementioned research. From this study evolved the "folded beam" concept. In this concept all diagonal folds or rib patterns were abandoned and a straight-forward parallel rib pattern was adopted.

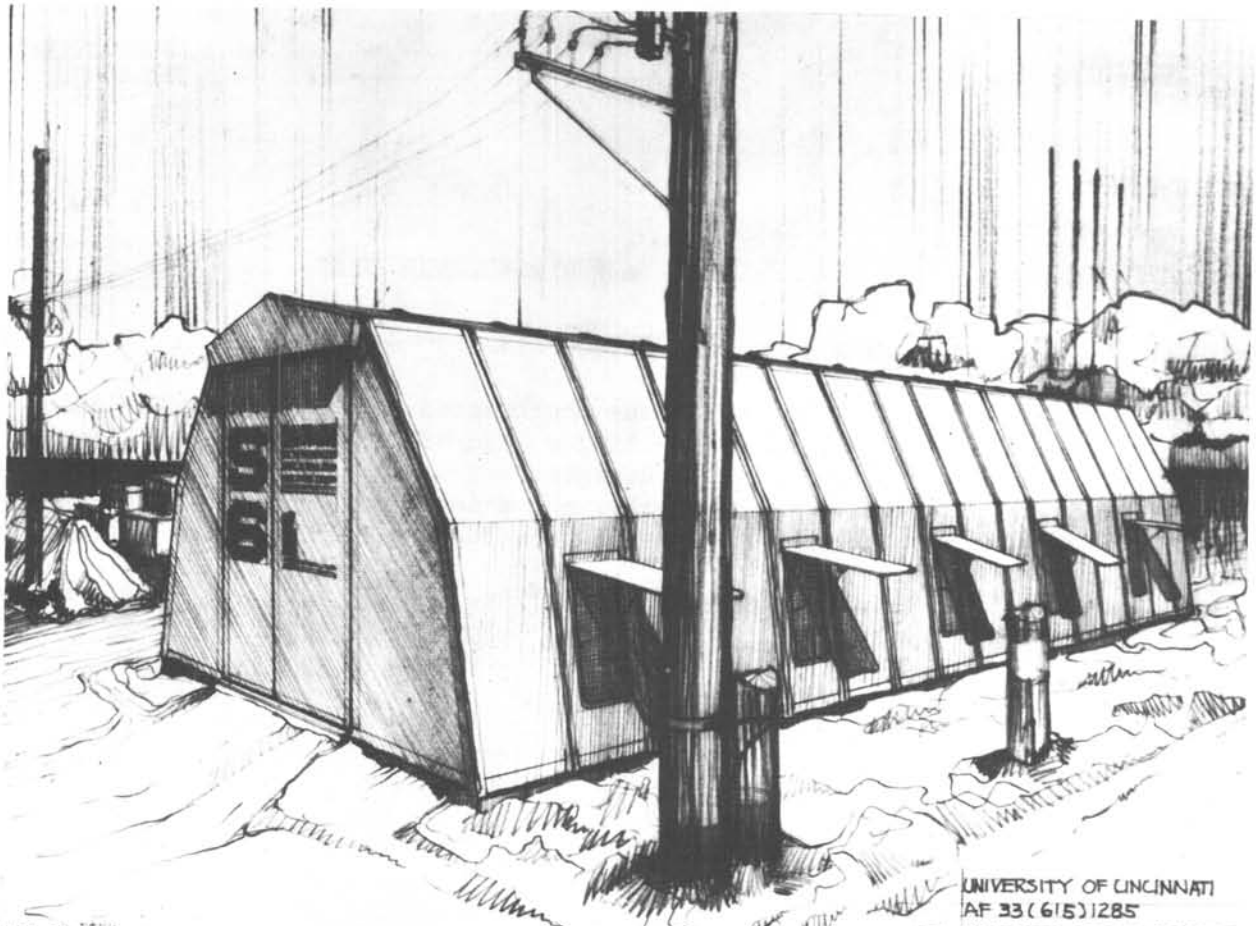


FIGURE 33. Rendering - Shelter using "folded beam" concept.

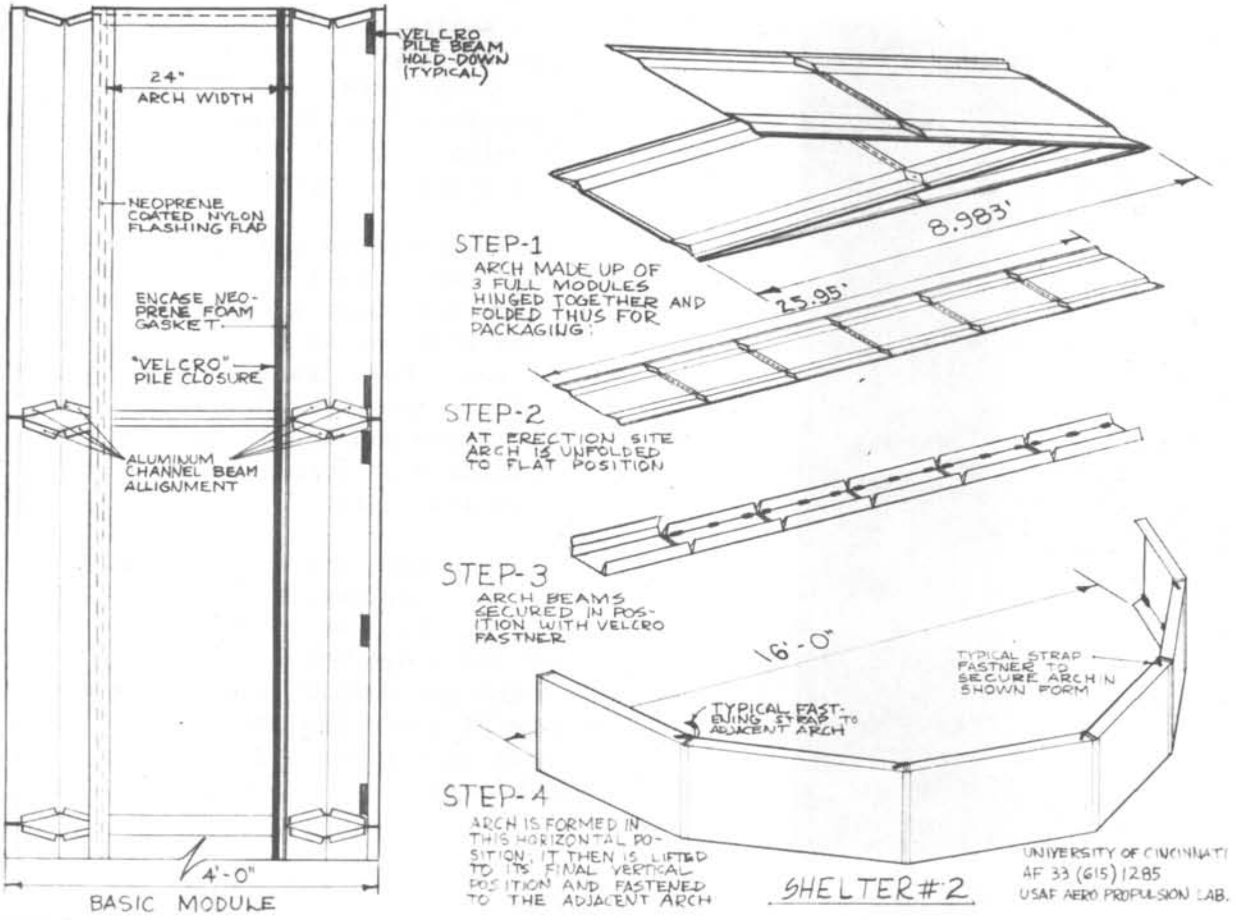


FIGURE 34. Drawing - Basic module and typical arch "folded beam" concept.

As in the previous concept, a typical arch was formed by Tedlar hinging together three rectangular panels each 4 ft. wide by approximately 9 ft. long. The outboard 12 inch strip on each side of the 4 ft. wide module was scored so that, when folded, a rigid triangular-section beam was formed. The beam is held in its folded position by means of previously attached strips of Velcro, aligned so that hook engaged pile when the beam was folded.

A typical arch is formed by following the four steps shown in Figure 34. For reinforcement in compression and for alignment in folding the segments into the arch, tongue and grooved light-weight aluminum channels cover the edges of the diamond-shaped openings in the module (See Figure 34). 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"

FIGURE 35. Uniform load test single "folded beam" arch.

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.

The details described above and in Figure 34. were worked out in full size typical sections and in two full size arch tests. Though it was realized that, as in Shelter #1, a complete shelter would have greater strength than a test of a single arch would show, a single arch was constructed and loaded to failure. This occured after a uniform load of 6 lbs. per sq. ft. was applied. (See Figure 35)

In the second test the middle 2 ft. of a double 4 ft. arch was loaded. It carried a load of 10 lbs. per sq. ft. At this loading vertical deflection at the ridge was 1 3/4". It was left loaded overnight and failed sometime during the night. Figure 36 shows the second test. 3 M Scotch filament tape gives added tensile strength at joints.

FIGURE 36. Uniform load test two attached "folded beam" arches.

FIGURE 37. Shelter # 2 Folding beams in test erection.

FIGURE 38. Shelter # 2 Test erection at University of Cincinnati.

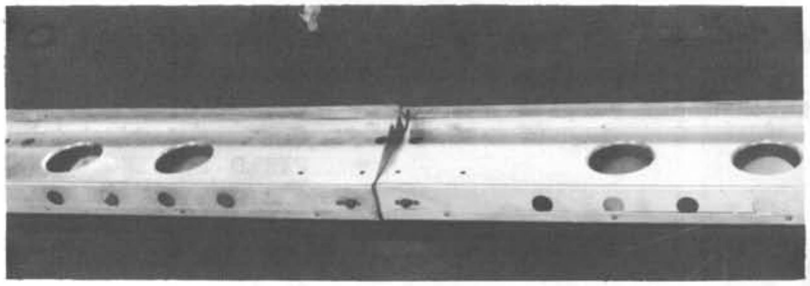


FIGURE 39. Shelter # 2 Aluminum grade beam typical joint.

CONSTRUCTION OF SHELTER # 2.

The "folded beam" approach was selected for the second of two shelters to be constructed under the Amendment to the Contract. This structure was to be 32' long x 16' wide. End panel requirements were similar to those for Shelter # 1.

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 aluminum (See Figure 39).

Exterior and interior protective finish (after extensive trade-off tests): 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.

FIGURE 40. Shelter # 2. Langley AF Base, Va. Packaged Shelter left: basic shelter, right: insulation kit.

FIGURE 41. Shelter # 2. erection of "folded beam" arches, Langley AF Base, March 1965.

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

Windows: rectangular Tedlar hinged cut outs in Fome-Cor, screened inside, bi-fold grometted shutters riding on Venetian blind operating cords.
Skylights: fixed 1/4" thick clear acrylic sheets.

FIELD TESTING OF SHELTER # 2

On 18 March, 1965 Shelter #2 was shipped by air to Langley Field AF Base for erection and testing. A five-man University team erected the Shelter in approximately three hours (15 man hours).

FIGURE 42. Shelter # 2 Erected shelter showing end with large doors.

FIGURE 43. Shelter # 2 Erected shelter showing end with small door, filler panels.

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 aluminum grade beams but not including stakes or tarpaulin) was 630 lbs. Insulation was packaged separately. Packaged shelter and insulation kit are shown in Figure 40. Erection time could have been reduced considerably had the site been more level thus making unnecessary some realignment of end treatment components on one end. Erection was accomplished in gusty weather so care was exercised in folding and carrying the lightweight arches.

Shelter # 2 remained in position at Langley for a period of one month showing no evidence of structural failure, leakage, or deterioration of materials or finish. During this period high winds and considerable rainfall provided a good weatherability test.

At time of writing the shelter is being returned to the University in anticipation of its being shipped to and exhibited at the Second Expandable Shelter Conference.

LARGE SHELTER CONCEPTS

As stated in the Introduction, the work under the contract includes developing of concepts for large shelters capable of housing fighter aircraft. Exploration of concepts for the large shelter were carried on concurrently with the preliminary studies of the small general purpose shelters. Work on the large shelter concepts was set aside during the period of construction of small Shelters # 1 and # 2 and have been resumed only during the month following completion of tests of Shelter #2.

INITIAL CONCEPT

The major approach followed in initial studies involved the use of trussed arches with a coated fabric (or lightweight sheet) covering. The concept is explained in renderings (Figures 44 and 45) which show the completed structure and a possible erection procedure.

The material used for the trussed arches would most likely be aluminum (or possibly magnesium) tubing although all preliminary models have utilized light rod stock.

The basic element in the arch in this concept is a "keystone" shaped element formed by rotating two trapezoided shaped frames up from a rectangular frame until a triangular section is formed. The keystone units would then be joined together to form the trussed arch. This sequence is illustrated in Figures 46, 47, and 48. Figure 49 shows a complete arch constructed at one-third scale.

The depth of the triangular section is determined as required for bending as an arched beam. The base width of the triangular section is determined as required for lateral stiffness. The rotating of the trapezoidal frames would bring together at the apex of the triangular section two tubes thus giving a double compression member at this point.

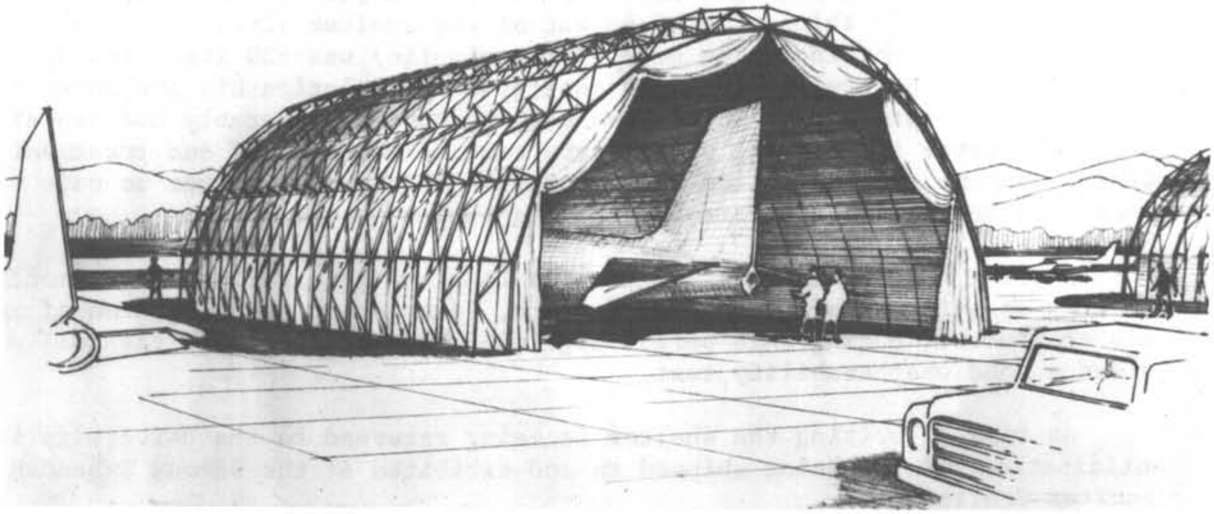


FIGURE 44. Rendering - hangar concept (50' span)

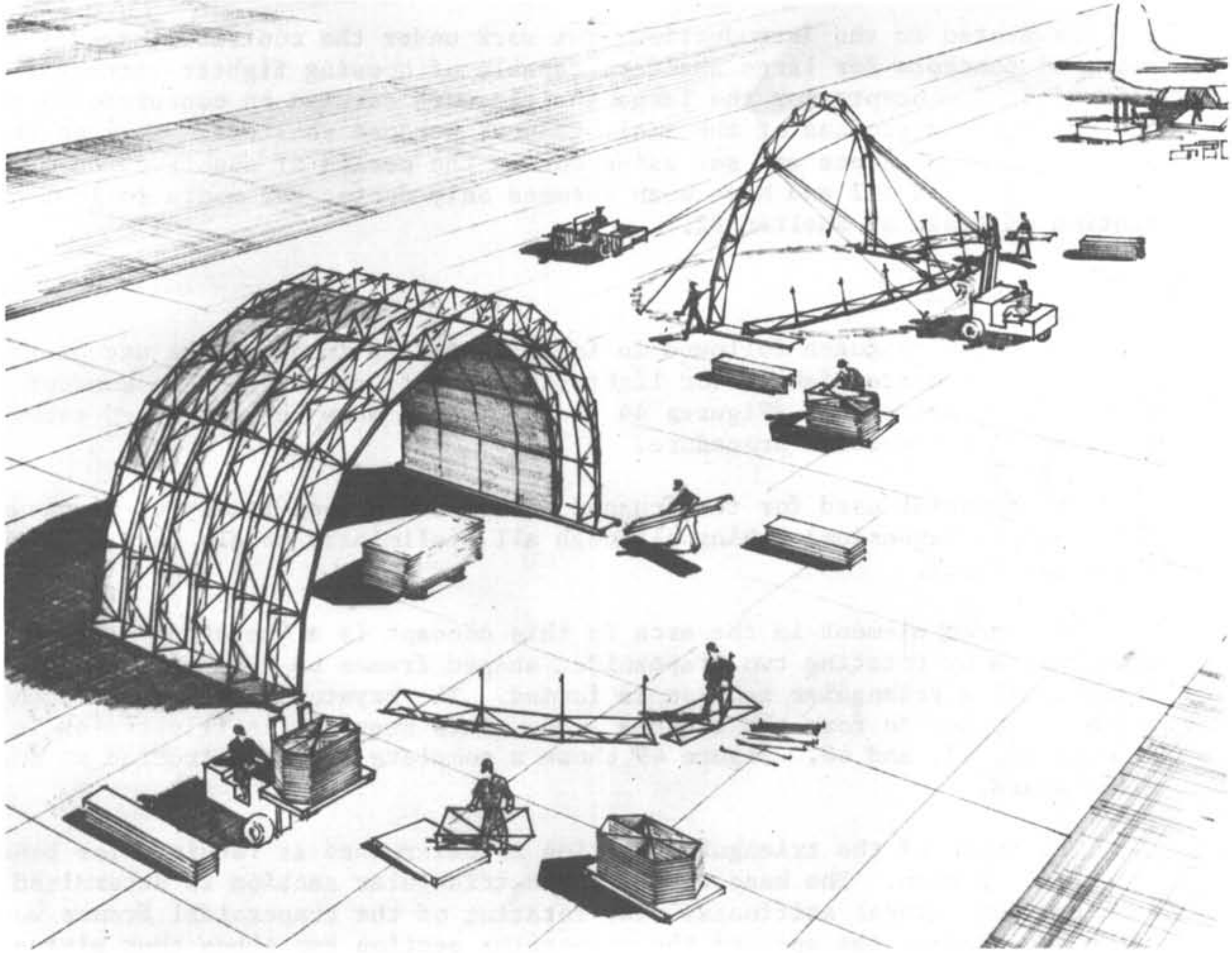


FIGURE 45. Rendering - hangar concept (erection procedure)

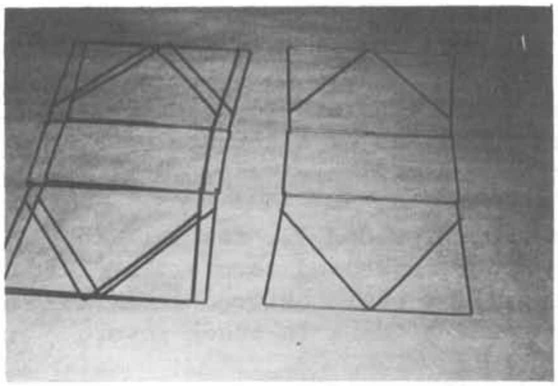


FIGURE 46: Welded rod hinged trapezoidal frames in flat position.

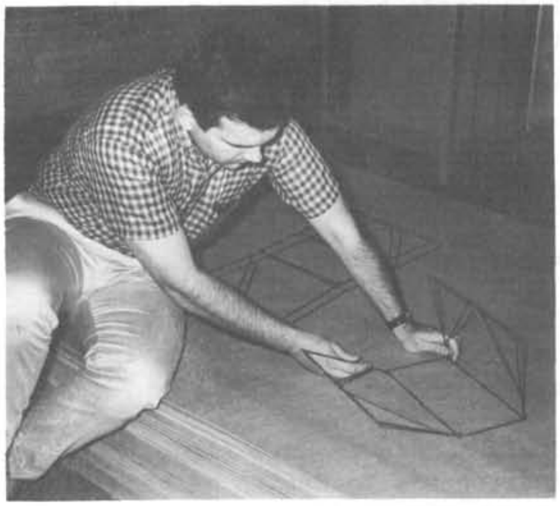


FIGURE 47: Frame being rotated into triangular "keystone" section.

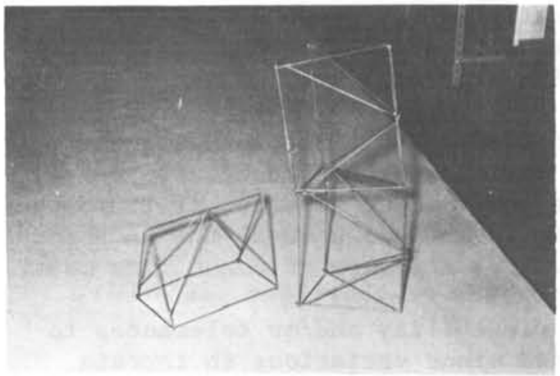


FIGURE 48: Left: "keystone" unit. Right: two units joined.

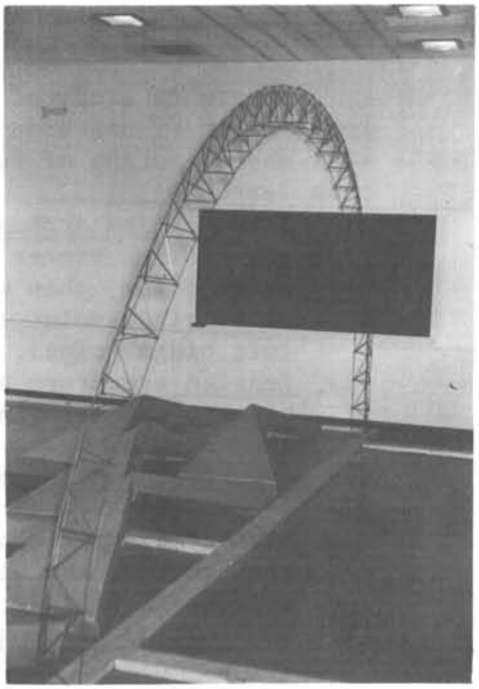


FIGURE 49: Hangar concept - one third scale trussed arch formed from welded rod "keystone" units.

This approach has the following features:

(1) Structural members can be shipped flat.

(2) Arches may be set up adjacent to each other or spaced apart with purlins and wind braces.

(3) Power winches would probably be the only erection equipment necessary.

(4) The erected trussed arch would form a built-in ladder for the erection crew.

Under study at present are attachment devices for the arch components, purlin and cross bracing design, types of covering material and attachment methods for same, ground anchoring and grade beam design. Detailed structural design and material specification will follow.

ALTERNATE CONCEPTS

Return to study of the large shelter after construction of small shelters #1 and #2 has been featured by a reexamination of alternate concepts that may be worthy of further investigation. Among these approaches are ones featuring:

(1) Three hinged arches in which arches are shipped K.D., fastened together with center hinge point blocked up, anchored securely at left hinge point, then winched upward by pulling cable between left and right hinge point (with right hinge point sliding in track toward left hinge point).
(2) Tension structure of hexagonal plan (or three sided ends on long structure) featuring compression masts and tension lines supporting fabric skin.
(3) Compression arch consisting of shell made of corrugated sheet plastic overlapped at ends and sides, bolted together with spring-loaded thumbscrew-type connectors, and erected by rigidly fixing one side of structure and winching other side's grade beam toward the fixed side until desired configuration achieved.
(4) Combination segmented trussed arch and rigid insulation panel construction.
(5) Space frame.

SUMMARY

The author and other members of the team have concluded:

1. 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.

2. 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.

3. 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 weathertightness, structural unity, total package weight, and man hours consumed in the erection process.

4. 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).

5. 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.

6. 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.