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APPLIED ENGINEERING RESOURCES,
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AIR FORCE CIVIL ENGINEERING CENTER

SEPTEMBER 1975

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AIR MOBILITY SHELTER CONCEPTUAL STUDY

APPLIED ENGINEERING RESOURCES, INC.
112 EAST DE LA GUERRA STREET
SANTA BARBARA, CALIFORNIA 93102

SEPTEMBER 1975

FINAL REPORT: JULY 1974 - APRIL 1975

Approved for public release; distribution unlimited.

AIR FORCE CIVIL ENGINEERING CENTER
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
FLORIDA 32403

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This report summarizes an evaluation of existing air transportable shelters and identifies areas in which improvements can be made in the future.

In general, the study suggests that existing shelters have been quite successful with respect to: air transportability, overall weight, rapid erection and striking, and adaptability to diverse uses. Existing shelters have not, however, been totally (Con't)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) (block 20) satisfactory with respect to durability, repairability, compatibility with extremes of environment, and commonality of elements. The majority of these problems have been due to limitations in the materials and manufacturing techniques utilized, rather than from any basic shortcomings of the shelter concepts.

Accordingly, this study suggests that use of premium-quality materials, advanced manufacturing techniques, and more conservative design allowables will result in superior shelters in the 1980's.

Examples of 1980's materials suggested for their high specific strength, stiffness and durability are: epoxy resins reinforced with aramid fibers such as Kevlar; woven Kevlar fabric; epoxy, or polycarbonate foams reinforced with chopped graphite, aramid, or refractory oxide fibers; and ultra-high molecular weight polyethylene. Filled elastomers are suggested for weather resistance and RFI/EMI control. All of these materials lend themselves to highly automated manufacturing methods.

Several types of "add-on" kits are suggested.

FOREWORD

This report was prepared by Applied Engineering Resources, Inc. under contract F29601-74-C-0112, job order 21012002, with the Air Force Civil Engineering Center, Tyndall AFB, FL. (The effort was initiated and managed for most of the period by the Air Force Weapons Laboratory, Kirtland AFB, NM.)

This report summarizes work done between July 1974 and April 1975. Capt Galen C. Bessert was the project engineer at AFWL. After transfer to AFCEC, Mr. James R. Van Orman became the project engineer.

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This report has been reviewed by the Information Office (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

James R. Van Orman
JAMES R. VAN ORMAN
Project Engineer

STERLING E. SCHULTZ, Lt Col, USAF
Director of Facilities Systems

ROBERT E. BRANDON
Technical Director

ROBERT M. ITEN, Colonel, USAF
Commander

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SECTION I
INTRODUCTION

1.1 GENERAL BACKGROUND AND STUDY OBJECTIVE

The concept of equipping a forward or bare base rapidly with all facilities and equipment required to support tactical air operations is highly dependent upon the availability of shelters which are capable of being air transported while requiring the least possible aircraft capacity, both in terms of weight and volume. These shelters must be durable and able to meet the minimum requirements of the use for which they are intended. Recent Air Force emphasis has been directed to the "Bare Base" concept, using shelters which serve as containers for mission support equipment while in transport and which expand to usable structures at the site. Thorough testing has revealed a number of limitations in these shelters. In addition, in the years since their design, the state of materials and manufacturing technology has made continuous advancements. Both of these facts dictated (1) a reassessment of the current Bare Base shelter system, and (2) conceptualization of structures which beneficially use current and forecasted improvements in materials and structural technology. The specific objective of this study was to evaluate present Air Force mobility shelters and related shelter concepts and criteria, and to develop a conceptual integrated system of air mobility shelters which will more completely satisfy these criteria by using improved materials and manufacturing technology possessing a high probability of being available in the 1980's.

1.2 OVERALL STUDY SCOPE

The study was accomplished in two phases. Phase I of the study was a detailed review of major existing air mobility shelters for the purpose of evaluating the advantages and shortcomings of materials and manufacturing technology used in their fabrication. Phase II consisted of a broad review and analysis of materials and structural technology, applicable to air transportable shelters, which are currently just beyond the state of the art and that are predicted to be available in the 1980's. This phase included a selection of the best of these materials for possible incorporation into a conceptual design of a family of advanced air mobility shelters.

1.3 GENERAL STUDY TECHNICAL APPROACH AND REQUIREMENTS

Until as recently as the 1960's, the tent was essentially the only universal, transportable military shelter available. In the early 1960's, an Air Force study was conducted to determine which existing portable facilities required to support highly mobile tactical air forces during deployment were inadequate to accomplish this objective at that time. It was concluded that the existing "Harvest Eagle" mobility equipment was entirely insufficient to provide the necessary facilities to support sophisticated fighter aircraft found at advanced tactical operating bases. As a result of this conclusion, the Bare Base Equipment System Program Office was established with the objective of developing and procuring an entire system of air mobility equipment. This system includes shelters, all utilities, heating and ventilation equipment, vehicles and numerous other items necessary to support an advanced base. This equipment was developed within a relatively short time span in an effort to satisfy a then urgent requirement to demonstrate the effectiveness and practicality of the bare base concept. The capability of the Bare Base system has been effectively demonstrated and it has provided a mobility capability previously unavailable in any form. However, if for no other reason than the storage life of the Bare Base shelters is estimated at 10 years, an effort to develop an improved new system to replace the Bare Base system is necessary. Beyond merely replacing equipment which will have worn out, it is also believed that significant advancements can be made to improve and eliminate certain deficiencies of the existing shelters and other equipment of the Bare Base system.

In the last 25-30 years, a considerable effort has been expended by various organizations throughout the government and private industry to develop portable shelters which are lightweight and rapidly erectable. The basic motivation for these efforts was to provide an enclosed space with a controlled environment, at low cost, and using as little effort or time as possible for deployment and erection. This motivation is also of interest to the United States Air Force, but the Air Force also requires that the shelters not only be portable, but also air transportable to facilitate the rapid deployment of tactical air forces to any geographical region in the world.

The tent continues to be proposed as a solution to many requirements for portable shelters. However, investigations and studies with the tent have revealed a number of deficiencies that make it undesirable as a shelter. Basically, large tents are relatively difficult and time consuming to erect, not very durable over extended periods of time, susceptible to wind damage, and do not provide an enclosed environment which can be efficiently controlled and maintained. The advantage offered by the tent, a relatively small package which can be expanded to provide a sheltered floor space many times the original volume, is very desirable. However, at the present time, tents, within the current and projected stages of their capabilities, do not provide the basis for a universal type or family of air mobility shelters the Air Force is seeking.

Extensive research has also been conducted in the area of portable rigid-wall structures, both expandable and non-expandable. Current Bare Base shelters are essentially expandable rigid-wall structures. Although these shelters satisfy the current requirements for a system of air transportable shelters and provide the Air Force with air mobility capability, these shelters are not considered the ultimate solution. For example, the high cost per square foot of floor area, insufficient insulating characteristics, and the susceptibility to panel delamination which has been a problem in all shelters built with sandwich panel construction could be corrected or improved with new materials and manufacturing techniques. Although Bare Base shelters have advanced the state of the art of air transportable facilities, they possess deficiencies which partly stem from the requirement to provide demonstration shelters in a relatively short period of time and the limited opportunity for investigation of the optimum method of shelter fabrication. One noticeable result of the rapid design is the number of separate parts and components that are included in the shelter. The large number of parts increases the labor costs of the shelters because of the number of hand assembly operations involved. The elimination of the large number of parts in new designs would reduce the manufacturer's labor costs, help to decrease the initial cost per square foot of shelter and reduce the maintenance and supply costs. A more exhaustive investigation of materials and structural technology applied to this type of shelter could eliminate these deficiencies and provide a better, less expensive family of shelters.

Air-inflatable structures have also received considerable attention and study. These shelters are essentially tents which use air for support instead of rigid framework. Like tents, they possess the advantage of providing a shelter of considerable size from a relatively compact shipping package. They also suffer some of the same disadvantages as tents, such as susceptibility to wind damage. In addition, experience with inflatable structures has revealed a tendency for them to collapse from panel separation and other causes of loss of air. As with tents, the basic concept of the air-inflatable shelter remains valid and warrants further investigation as a potential solution for particular structures, but in general not for development into a family of future shelters.

Another area which has received attention over the last 10 years is that of shelters constructed of foam. Various concepts have been considered for building foam shelters. The Air Force has previously funded the development of prototype equipment to generate foam-in-place shell structures. This process demonstrated some potential for providing rapidly erectable shelters at a relatively low cost. Further investigation of this area to improve, refine and develop this concept has pointed out various logistic, shelf life, and erection problems. These problems, coupled with current requirements for controlled temperatures, forms, equipment, etc., do not lead this area into development of families of future shelters.

However, combinations of the above approaches, using advanced materials and technology can offer significant performance advantages.

1.4 CRITERIA FOR ANALYSIS, EVALUATION, AND CONCEPT DEVELOPMENT

In all concepts developed, the fact was kept in mind that the equipment and facilities comprising existing air mobile basing systems is subdivided into five general categories or subsystems: Shelters, utilities, vehicles, synthetic surfacing, and support subsystems. This report primarily addresses the area of shelters, with the provision that shelter concepts developed be compatible and integratable with both current and conceivable future air mobile basing subsystems.

The analysis and evaluation of existing shelter concepts and advanced concepts includes consideration of the following typical shelter characteristics:

1. Expansion ratio; i.e., from shipping configuration to deployed configuration.
2. Ratio of shipping weight to shipping volume.
3. Simplicity of erection and handling.
4. Durability of materials and structural integrity after extended use.
5. Maintainability.
6. Adaptability to diverse uses.
7. Thermal characteristics.
8. Commonality among shelters.
9. Cost, both initial and life cycle.

Other related measures, or variations of the listed characteristics, were also considered. In addition, certain specific requirements were stated by USAF for advanced shelters:

1. The entire system of shelters is to be air transportable and compatible with materials-handling equipment and roller-conveyor systems; wherever possible, the shelter systems shall also be compatible with the international containerized (ISO) shipping standards. Low weight and cube are a primary design factor.
2. Materials used in fabrication of shelters shall not support combustion and shall be electrically nonconductive.
3. Once in place, the shelters should be capable of being sprayed or otherwise covered to provide hardening for passive defense.
4. Shelters should possess the best practicable thermal characteristics and be capable of being easily heated or cooled, including the high and low temperature extremes. The following environmental conditions from the current Bare Base system specification were used in this study:
   a. Temperature: minus $50^{O}F$ to plus $125^{O}F$, plus a solar load such that the outer skin reaches a temperature of plus $200^{O}F$; exposure at any one time will not exceed 4 hours at the high temperature.
   b. Humidity: 0 to 100 percent.
   c. Wind: steady wind velocities of 60 knots and gusts of up to 90 knots with wind carrying sand, snow, sleet, and/or dust.
   d. Altitude: sea level to 10,000 feet; in addition, the shelter must survive altitude and pressure changes experienced from shipment by aircraft operating from sea level to 45,000 feet.
   e. Snow load: 40 pounds per square foot.
   f. Rainfall: probable extreme precipitation (refer to Paragraph 2.5 in MIL-STD-210).

g. Salt fog: salt content of the airborne moisture shall be from 0 to 5 percent by weight.

5. Shelter lights, heating, and cooling systems should be organic to the shelter if at all possible; maximum use of natural ventilation and native materials should be made wherever possible.
6. Materials used in construction of shelters shall be noncorrosive to minimize damage caused by the elements during storage and use.
7. Shelters should be designed to have an inherent chemical/biological/ protective capability to ensure the survivability of the deployed forces.
8. In addition to the requirements stated above, the following alternatives were also considered to select the more desirable shelters:
   a. Reusable versus disposable facilities.
   b. Single all-weather shelter versus a basic shelter with optional add-ons for different climatic zones.
   c. The ability of shelter materials to provide RFI and EMI shielding integrally or with a minimum of alterations.

Current air mobile shelters, and other portable shelters and shelter concepts, were examined and classified as to their basic capability and demonstrated performance relative to all of the above criteria, requirements, and considerations. This evaluation was intended solely to identify high-payoff potential detail design areas and overall shelter concepts to which advanced materials and structures technology might be applied to produce shelters superior in performance relative to current concepts.

SECTION II
REVIEW OF EXISTING SHELTERS AND CURRENT SHELTER CONCEPTS

2.1 INTRODUCTION

Phase I of the Air Mobility Shelter Conceptual Study had two primary objectives:

1. Review the general requirements for operational performance, interface requirements, and cost factors of current air mobility shelters.
2. Review existing shelters and current shelter concepts and determine the advantages and disadvantages of these shelters and concepts relative to the general requirements.

The information and knowledge thus acquired and developed would then be the baseline from which to study and develop advanced concepts for air mobility shelters which utilize projected 1980's time frame improvements in materials, manufacturing methods, and structural elements.

An initial, broad review of currently-available shelters, both military and commercial, leads to the following observation: There are many current shelters and shelter systems available today that are identified by their producers or users as any or all of the following:

- Lightweight
- Expandable
- Air transportable or easily transportable by various modes
- Modular
- Universal
- Relocatable
- Field erectable
- Rapidly erected, easily erectable.

When current general requirements for air-mobile military shelters are reviewed, as typified by the required "system characteristics" of the shelters in the U. S. Air Force Bare Base Equipment System -437A (Page 12, Ref. 1), the same, or similar, requirements, are noted. References 2 and 3 cite similar general requirements for mobile shelters. Therefore, it is that general military shelter requirements may be satisfied by current shelters and shelter concepts not previously considered for military application. The specific utility of a given shelter for a particular application can only be ultimately evaluated, however, on its simultaneous satisfaction of general requirements, such as loads, dimensions, weights, and other physical requirements.

Conversely, the failure in service of a particular shelter, in some respect, due to a design detail deficiency, should not be the rationale for rejecting the general shelter concept. This is especially important if the shelter concept is particularly good in the satisfaction of general requirements. Therefore, the Air Mobility Shelter Conceptual Study Phase II shelter review is presented in this report section by (1) first categorizing current shelter general concepts or types, and (2) categorizing, somewhat independently of shelter type, current shelter design details or elements. Operational, interface, and deployment approaches are then reviewed, as are cost factors. Section III of this report covers evaluation of the advantages and disadvantages of current general concepts, detail element concepts, and operational approaches relative to current requirements.

2.2 DATA SOURCES

The Phase I study activity, Evaluation of Existing Concepts, was allocated under the study contract a period of eleven weeks, including preparation of a summary briefing given to U. S. Air Force personnel at Kirtland AFB. This short evaluation period, and the availability of an extensive body of technical data on shelters, dictated that the evaluation concentrate on review of existing data on current and previous shelter development and contact with personnel with current or previous direct involvement in shelter programs, rather than attempt to conduct any sort of shelter test program or extended new statistical evaluation.

In general, data was acquired from military-service sources, other government agencies, shelter suppliers, and material and component suppliers. Data was located by use of the USAF-furnished initial bibliography (in the Request for Proposal); National Technical Information Service Index; Defense Documentation Center Index; NASA Star Reports; Applied Science and Technology Index; and secondary references. This data was reviewed and an informal but extensive working index was prepared, categorized as follows:

- Shelter concept, by type
- Service experience or test experience, by shelter type
- Analysis or comment on general and/or detail design requirements
- Cost factors
- Technology information, current concepts
  - Materials and processes
  - Structures and approaches
- Operational and interface approaches

It was this data categorization that exposed, in a massive amount of data, the significant recurring evidence of opinions on the relative merits of the various shelter types and detail design approaches which form the basis for the evaluations of Section III of this report. The REFERENCE AND BIBLIOGRAPHY section at the end of this report lists the shelter data reviewed.

In addition to data review, field trips were taken to the following organizations for the purpose of general discussions on advantages and disadvantages of particular shelters:

1. Naval Civil Engineering Laboratory, Port Hueneme, California (Mr. R. Seabold).
2. Air Force Civil Engineering Center, Tyndall Air Force Base, Panama City, Florida (Mr. R. Van Orman).

3. U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir Virginia (Mr. M. Wilkins).
4. U. S. Army Natick Laboratories, Natick, Massachusetts (Mr. J. Siegel).
5. Hanscom Air Force Base (Mr. R. Karlson).
6. Bare Base SPO, Wright-Patterson Air Force Base, Dayton, Ohio (Mr. R. Matzko).
7. Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico (Capt. G. Bessert; Major Warren).
8. Brunswick Corporation, Marion, Virginia (Mr. D. Eaton).
9. Goodyear Corporation, Litchfield Park, Arizona (Mr. T. Cameron).

In addition to discussions on these trips, shelters were observed being deployed, struck, or fabricated, and first-hand observations were made of design details on numerous components.

Additive to the shelter-related data and trips noted above were the acquisition and review of several hundred data sheets, technical data sheets and journal articles on recent and projected materials and structures developments either used now on shelters or potentially usable. In total, a very broad review of current and potential practice was conducted. Several references of this type are included in the REFERENCES AND BIBLIOGRAPHY sections of this report, if particularly needed to support study conclusions; however, because the majority were reviewed for exploratory purposes only, all materials references are not necessarily included.

2.3 CATEGORIZATION OF EXISTING SHELTER TYPES

Categorization of shelter "types," or "concepts," must be done with relative precision, because otherwise the comparison between two apparently similar, but not actually comparable, concepts might be made. As a simple example of this, it would be inappropriate to rate the deployed/stowed volumetric expansion ratio (11) of the Bare Base Expandable Personnel Shelter as superior "in concept" to that of the same ratio (2.7) for the Expandable Shelter Container, when a more precise categorization would reveal that the latter shelter has internal storage area remaining in the stowed mode, and is really a different concept in that regard. Nevertheless, one classification system (Reference 4) identifies both as "hardwall expandable."

Similarly, classification and evaluation of shelter concepts by end use can obscure the real relative advantages and disadvantages of a shelter. For example, the "Atco Foldaway Building" and the "Bare Base General Purpose Shelter" are both classified in Reference (4) by use as "general purpose," and are built up from components, and yet one is classified as hardwall expandable and the other as a component type, and yet they are not at all similar in any physical regard. The same comment on classifying shelters by use could be made on air-inflatable hangars versus Bare Base component hangars; i.e., description of common use does not denote any basic similarity of concept.

2.3.1 Current Shelter Classification Systems

Reference (4) classifies shelters into the following categories:

1. Hardwall non-expandable
2. Hardwall expandable
3. Component
4. Inflatable
5. Tents
6. Disposable
7. Other

This is a suitable classification for cataloging, but should be expanded when developing or evaluating new concepts, as described later in this report (see Subsection 2.3.2).

Reference (5) organizes shelters by using organization in the catalog. Type classification is by application of one or more of the following designators: Rigid, non-rigid, pole supported, frame supported, air supported, air inflated, expandable, non-expandable, variable size. But the addition of "component," "disposable," and several other designators, and structuring a hierarchy of these designators, is required to fully classify shelters.

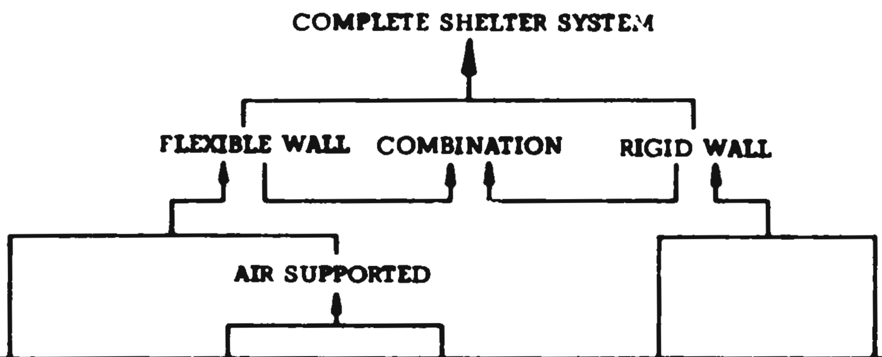
A more complete approach to classifying shelter concepts, and one which is more useful in developing new concepts, is presented in Reference (2) on Pages A-1 through A-5. In essence, the shelter-type designators of References (4) and (5) are put into a matrix, which allows a more precise method of classifying shelters by use of as many classifiers as required.

The approach to shelter categorization of Reference (2) was used in the review of existing shelters, and, more importantly, was also the basis for examining new combinations, or concepts. This subsection presents the shelter categorization method used in this report.

2.3.2 Suggested General Categorization System

Figure 1 illustrates the categorization approach. The two most evident things in this categorization are:

1. Without even further defining specific mission uses of shelters, this matrix displays 55 distinct approaches to portable shelters that either exist, are in development, or have been suggested based on some success with the technology involved; this large number also does not include combination rigid-wall/flexible wall buildings, of which several types were found.
2. Neither the categorization system of Figure 1, or of References (2), (4) and (5), which are certainly extensive and complex, actually make a completely distinct differentiation between air-mobile, relocatable buildings, and many types of existing or proposed "permanent" buildings.



A. FRAMEWORK SUPPORTED	B. PRESSURIZED INTERIOR	C. PRESSURIZED WALL	D. NON-EXPANDABLE	E. EXPANDABLE	SHELTER CHARACTERISTICS
* A-1	B-1	C-1	D-1	E-1	SEPARATE COMPONENTS ASSEMBLED IN FIELD
A-2	B-2	C-2	D-2	E-2	SELF-CONTAINED, FOLDOUT OR INFLATED
A-3	B-3	C-3	D-3	E-3	MAJOR ELEMENTS FABRICATED IN FIELD
A-4	B-4	C-4	D-4	E-4	REUSABLE, ALL MAJOR ELEMENTS
A-5	B-5	C-5	D-5	E-5	DISPOSABLE, ALL MAJOR ELEMENTS
A-6	B-6	C-6	D-6	E-6	FUNCTIONS AS CONTAINER WHEN STOWED
A-7	B-7	C-7	D-7	E-7	NO FUNCTION AS CONTAINER WHEN STOWED
A-8	B-8	C-8	D-8	E-8	MODULAR - CAN MATE WITH SAME OR OTHER TYPE UNIT
A-9	B-9	C-9	D-9	E-9	NO PROVISION FOR MODULAR USE
A-10	B-10	C-10	D-10	E-10	ORGANIC UTILITIES MISSION PROVISIONS
A-11	B-11	C-11	D-11	E-11	NO ORGANIC UTILITIES MISSION PROVISIONS

* SHELTER TYPE DESIGNATOR FOR TABLE 1 AND TABLE 5

Figure 1. Shelter Categorization

In fact, many "prefabricated" industrial building systems and "modular, factory-built" residential buildings are similar in concept in many respects to transportable, relocatable shelters. The ultimate distinction between permanent and portable buildings is really one of degree of optimization of building design in such physical areas as:

- Relative match of the knockdown, or stowed, shelter's dimensions with the best dimensions for a particular carrier.
- Weight.
- Minimizing the site or foundation preparation required for the building.
- Minimizing the skill levels and total manhours required for erection or striking.

So it is the building user who must decide and define whether a building is air-mobile, by specifically defining the above noted and similar requirements.

In the Air Mobility Shelter Conceptual Study Phase I shelter review, the objective was to examine relative advantages and disadvantages of concepts, as preparation for developing advanced concepts. Therefore, a broad review of shelter types was made, but without rejecting or criticizing a concept just because it obviously did not meet the specific detail requirements of the Study.

Table 1 is a simplified extraction from the indexed shelter data review that keys a shelter type of Figure 1 to one or more typical examples of a shelter, and one or more references that describe the concept, and specific technical data and discussion of benefits and disadvantages. (Section III of this report presents the specific data on these shelters that is relevant to evaluating shelters and establishing criteria for advanced shelters.)

A very complete review of current shelter concepts was conducted and should a particular shelter not be noted in the "Example" column of Table 1, or identified in the cited references, that "missing" shelter will not have been substantively different in concept, or even particularly unique in any detail of construction. Many shelters were observed and/or discussed for which no meaningful printed data could be reviewed.

Specific discussions and conclusions about current types of shelters are presented in the following subsections and in Section VI . However, even a cursory review of the shelter types noted in Figure 1 and of the data referenced in Table 1 leads to the following preliminary conclusions:

1. Conclusion: When a rigorous classification of shelters is made, it is then seen that almost every conceivable basic concept and arrangement for making and/or erecting shelter has received from some to considerable attention.
2. Conclusion: Within a shelter type, however, the materials of construction, structural elements, manufacturing methods, and service experiences, if any, are remarkably uniform; variations are found primarily in design details.

Conclusion No. 2, above, is the subject of the following subsection.

TABLE 1. SHELTER TYPES REVIEWED

SHELTER TYPE DESIGNATOR (See Figure 1)	EXAMPLE	MAJOR REFERENCE DATA FOR EXAMPLE(S) AND OTHER SHELTERS OF TYPE
A-1	Most Army tents	4,5
A-2	Some Army tents	4,5
A-3	None located, but concept evaluated	2,17
A-4	Most Army tents	4,5
A-5	None located, but concept evaluated	2,17
A-6	None located	--
A-7	Most tents	4,5
A-8	Some military tents	4,5
A-9	Some military tents	4,5
A-10	None located	--
A-11	All tents reviewed	4,5

TABLE 1. SHELTER TYPES REVIEWED (CONTINUED)

SHELTER TYPE DESIGNATOR (See Figure 1)	EXAMPLE	MAJOR REFERENCE DATA FOR EXAMPLE(S) AND OTHER SHELTERS OF TYPE
B-1	None located, but concept evaluated	2,17
B-2	All located are this type	4,5,20
B-3	None located	--
B-4	All reviewed are this type	4,5,20
B-5	None located, but concept evaluated	2,17
B-6	None located	--
B-7	All reviewed	4,5,20
B-8	Must WARD (inflatable portion) shelter	5
B-9	Most reviewed	4,5
B-10	Must WARD system	5
B-11	Most reviewed are this type	5

TABLE 1. SHELTER TYPES REVIEWED (CONTINUED)

SHELTER TYPE DESIGNATOR (See Figure 1)	EXAMPLE	MAJOR REFERENCE DATA FOR EXAMPLE(S) AND OTHER SHELTERS OF TYPE
C-1	None located	--
C-2	Hughes air inflatable electronic shelter	5,20
C-3	None located	--
C-4	All reviewed	2,4,5
C-5	None located, but concept evaluated	2,4,5
C-6	Hughes air inflatable electronic shelter	5,20
C-7	Hughes air inflatable electronic shelter	5,20
C-8	Most reviewed are this type	2,4,5,20
C-9	Bird air shelter	2,4,5
C-10	Hughes air inflatable electronic shelter	5
C-11	Most reviewed are this type	2,4,5

TABLE 1. SHELTER TYPES REVIEWED (CONTINUED)

SHELTER TYPE DESIGNATOR (See Figure 1)	EXAMPLE	MAJOR REFERENCE DATA FOR EXAMPLE(S) AND OTHER SHELTERS OF TYPE
D-1	Seabee Quick Camp shelters	3,27
D-2	Not applicable	--
D-3	Not applicable	--
D-4	All are this type	2,4,5,6,27
D-5	None located, but concept evaluated	2,17,27
D-6	All are this type	2,4,5,6,27
D-7	None reviewed are this type	2,4,5,6,27
D-8	Seabee Quick Camp shelters	3,27
D-9	Most are this type	2,4,5,6,27
D-10	All reviewed are this type	2,4,5,6,27
D-11	None are this type	--

TABLE 1. SHELTER TYPES REVIEWED (CONCLUDED)

SHELTER TYPE DESIGNATOR (See Figure 1)	EXAMPLE	MAJOR REFERENCE DATA FOR EXAMPLE(S) AND OTHER SHELTERS OF TYPE
E-1	Bare base hangar	4,5,7,16,17,18
E-2	Bare base expandable shelter/container	2,4,5,7
E-3	None located	--
E-4	All reviewed are this type	2,4,5,7
E-5	None located, but concept evaluated	2,17,18,27
E-6	Bare base expandable shelter/container	2,4,5,7,10,16
E-7	Bare base hangar	1
E-8	LocArch	33,34
E-9	Bare base expandable personnel shelter	7,19
E-10	Bare base L/SAT shelters	9,10
E-11	Bare base hangar	4,5,7,16,17,18

2.4 CATEGORIZATION OF CURRENT SHELTER STRUCTURAL, MATERIAL, AND MANUFACTURING APPROACHES

It was found most useful to examine current shelters as regards the following individual elements:

1. Shape when deployed.
2. Load-bearing member types and materials used.
3. Joints, connections, and hinges.
4. Finishes for appearance or protection.
5. Insulation.
6. Other features.

Reference should be made to the Bibliography for specific technical details on specific shelters; the large number of shelters precludes cataloging this data in this report. In fact, References (4) and (5) are recommended for easy-to-compare summary data on a large number of shelters.

Table 2 is a matrix of the major shelter categories noted in Figure 1 (i.e., Types A through E), and most commonly noted general shape, or configuration of the deployed shelters, as determined from the referenced data of Table 1. While there were many exceptions to the noted configurations, conclusions as to the probable reasoning behind the configuration selection can be easily drawn, such as the listing on Table 2. These conclusions are generally supported by the reference data of Table 1.

The overall conclusion is that current shelter designs were in fact relatively constrained at the time of design by limited availability of materials and processes compared to the wider variety now being developed. This is reflected, as far as shelter shape is concerned, to designs not necessarily optimum from a utility standpoint (i.e., headroom, environmental resistance, load bearing efficiency, etc.). As a simple example of this, few framework-supported, or air-supported, flexible-wall shelters were identified that had a shape that allowed unrestricted headroom right up to the walls. As another example, the basic Locarch flat panel design was selected primarily for manufacturing efficiency and storage even though a slight panel camber would simplify installation.

2.4.1 Load-Bearing Member Types and Materials Used

Table 3 is a matrix of the major shelter categories noted in Figure 1, and the most commonly used structural elements and materials. When compared to the large variety of materials currently available and load-bearing elements currently in use for conventional building and structural applications, the examples on Table 3 are actually a relatively small number. In fact, the common genesis of current transportable shelters and current intermodal freight containers is apparent. The extensive use of sandwich panel construction and aluminum probably primarily reflects an emphasis on weight reduction, with good insulating characteristics being a secondary benefit. Framework-type structures are used less frequently; the most common application is in tents and in non-expandable rigid wall shelters (container type).

TABLE 2. SHAPES OF CURRENT SHELTER TYPES

SHELTER TYPE (See Figure 1)	MOST COMMON SHAPES	DRIVING FACTOR IN SHAPE DECISION
AIR-SUPPORTED, FLEXIBLE-WALL	Circular or near-circular arch	Material not available to take higher loads that would be required from higher pressures used in orthogonal shapes
FRAMEWORK-SUPPORTED FLEXIBLE-WALL	Near-circular arch or shaped to take out some loads in fabric	Materials not available to take higher loads that would be required from higher tension loads needed to take wind and snow loads
NON-EXPANDABLE RIGID-WALL	All flat panels; orthogonal walls	Materials available limit economical manufacture to flat shapes (compatibility with handling equipment also a major factor)
EXPANDABLE RIGID WALL (COMPONENTS)	All flat panels; most have orthogonal walls	Materials available limit economical manufacture to flat shapes (compatibility with handling equipment also a major factor)
EXPANDABLE, SEPARATE COMPONENTS	Almost all flat panels; most have orthogonal walls (notable exceptions: Bare Base hangar and GPS); some have ridge roofs	Materials available limit economical manufacture to flat shapes (compatibility with handling equipment also a major factor)

The materials and structure listing is not intended to be absolutely comprehensive nor a precise materials listing. The large variety of geometrical arrangements of frameworks and linkages found in shelters, for example, is not listed. Rather, it represents the commonality of materials approaches to a large variety of shelter concepts. Aging in storage, degradation of surfaces, delaminations, punctures, sweating, etc., are common problems reported in the references listing at the end of this report. If most current shelters were re-procured as of now with 1970's time-frame materials, the list of structures and materials would change very little, with the possible exception of introduction to shelters of already in commercial use, filled structural foams, and large integral-ribbed injection-molded thermoplastic panels.

2.4.2 Joints, Connections, Hinges

Table 3 also lists the most common materials for joints, closeouts, connections, hinge members, and structural fasteners other than adhesives.

The following is a summary of the most common mechanical approaches for these functions as used in current shelters:

1. Rivets are commonly used.
2. Closeouts, stringers, rafters, frameworks, connections, and hinges are almost universally fabricated separately and fastened on to the panel or curtain wall in separate operations (adhesives or rivets).
3. Custom aluminum or magnesium extrusions are widely used.
4. Most steel sections are standard, rather than shelter-peculiar.
5. Most fiberglass/epoxy elements are custom-designed.
6. The so-called "camloc" is in wide use in all types of expandable rigid-wall shelter concepts.

In general, no particular exception to these approaches is evident for any one shelter concept. However, there are some innovative approaches used on Bare Base shelters that are not found on other shelters, and which are not noted on Table 3, such as:

1. Velcro fasteners on fabric covers and flashing;
2. Crimped foamboard hinges.

Weather sealing of joints and connections is accomplished by either flashing or gasket type seals, or combination gasket-flashing. Field installation of tape-type flashing is relatively common in component type expandable shelters. Caulking in the field is infrequently used in the shelters reviewed. Sealing devices are separately fabricated and installed in a secondary operation, except in some tents where flashing is an integral part of the structural member. In general, poor service experience is reported on all aspects of sealing and flashing (References 6 through 22).

2.4.3 Finishes

On rigid-wall shelters, the application of finishes appears to be primarily intended to provide surface sealing for corrosion prevention and

TABLE 3. MATERIALS USED IN EXISTING SHELTERS

Note: X indicates material application in shelter type.

	FLEXIBLE WALL		RIGID-WALL	
MATERIAL AND/OR LOAD-BEARING ELEMENT	Framework-Supported	Air-Supported	Expandable	Non-Expandable
Sandwich panels-core:				
Paper honeycomb, partially filled with polyurethane foam			X	
Polyurethane foam, closed cell (3 to 6 lb/cu ft)			X	X
Dow styrofoam			X	X
Aluminum honeycomb			X	X
End-grain balsawood			X	X
Sandwich Panels-Skins:				
Aluminum			X	X
Fiberglas-reinforced epoxy (spray-up or prepreg sheets)			X	X

TABLE 3. MATERIALS USED IN EXISTING SHELTERS (CONTINUED)

MATERIAL AND/OR LOAD-BEARING ELEMENT	FLEXIBLE WALL Framework-Supported	FLEXIBLE WALL Air-Supported	RIGID WALL Expandable	RIGID WALL Non-Expandable
Sandwich Panels-Adhesives:				
Neoprene based, rolled on			X	X
Epoxy resin, rolled or sprayed on			X	X
Epoxy resin, film			X	X
Polyester film			X	X
Other Sandwich-Type Construction:				
Plywood/fiberglas			X	X
Plywood/aluminum			X	X
Plywood/steel				X
Expanded steel mesh and thermoplastic resin filler			X	
Foamboard (vinyl fact sheet and foam core)				

TABLE 3. MATERIALS USED IN EXISTING SHELTERS (CONTINUED)

MATERIAL AND/OR LOAD-BEARING ELEMENT	FLEXIBLE WALL		RIGID WALL	
	Framework-Supported	Air-Supported	Expandable	Non-Expandable
Load-bearing beams in framework, skin-stringer construction, joints, and panel closeouts:				
Extruded aluminum	X	X	X	X
Pultruded fiberglas	X		X	X
Molded fiberglas			X	X
Steel	X		X	X
Magnesium	X		X	X
Fabrics (covers or flashings):				
Cotton	X	X	X	X
Neoprene-coated nylon	X	X	X	X
Neoprene-coated fiberglas reinforced nylon	X	X	X	X
Polyester	X	X	X	X
Vinyl-coated nylon	X	X	X	X

TABLE 3. MATERIALS USED IN EXISTING SHELTERS (CONCLUDED)

MATERIAL AND/OR LOAD-BEARING ELEMENT	FLEXIBLE WALL Framework-Supported	FLEXIBLE WALL Air-Supported	RIGID WALL Expandable	RIGID WALL Non-Expandable
Fabrics (Continued)				
Tedlar® (dacron laminate)	X	X	X	X
Vinyl-coated cotton	X	X	X	X
Mylar®	X	X	X	X
Elastomer gaskets	X	X	X	X
Vinyl extrusions	X	X	X	X
Hypalon®-coated nylon or dacron	X	X	X	X

camouflage. While many of the urethane and rubber based finishes used do provide a degree of impact and penetration resistance, and insulation and reflectivity, these characteristics generally have not been the primary bases for selection.

Finishes are also used internally in rigid-wall shelters for slip or skid-resistance on floors, and for light reflection.

On flexible-wall shelters, the application of finishes, in addition to surface sealing, are often incorporated as an integral part of the fabric to provide an impervious membrane for chemical-biological agent exclusion, and in the case of air-supported structures, air leakproofing. No cases were found of separate application and independent use of finishes on flexible-wall shelters for structural load-carrying or penetration resistance.

No particular common pattern of bad field experience with finishes is reported in the literature (see References section of this report).

2.4.4 Thermal Insulation

The two basic and most common approaches to thermal insulation in current shelters are:

1. Insulation provided integrally with ceilings, walls, and floors by means of double-wall construction with a low thermal conductivity material between walls, or at least the addition of a layer of insulating material to the inner surface of walls.
2. Separable fly sheets or covers of insulating material, usually also incorporating a flashing type material; several examples of internally added zip-in covers were noted among the shelters noted or referenced on Table 1.

Table 3 lists the primary insulating materials used (polyurethane foam; styrofoam).

In the case of paper honeycomb core and plywood (core and laminate, respectively), significant insulation benefits are achieved as a side benefit to their primary function as structural elements.

No examples in military shelters were found that use field-applied, spray-on insulation or sealers. This approach is very common in the prefabricated commercial building field; however, re-use is a problem.

Reflective paint is used on many commercial portable buildings specifically for thermal control; this type of application is much less common in current military shelters; durability and performance experience has been relatively poor in military applications.

2.4.5 Other Shelter Features

Other features of current portable shelters were reviewed. Design approaches were examined in the following areas:

1. Floors
2. Foundations or supports

3. Windows, doors and vents
4. Provision of basic utilities
5. Interior space planning
6. Shipping and storage configurations
7. EMI isolation

To a large extent, these elements of portable shelters are configured specifically for the intended end use of the shelter. For example, floors are designed for personnel loads or equipment dead loads as are foundations or supports. Shipping and storage configurations reflect one particular transport mode, such as ISO water transport configurations.

Similarly, interior space planning and provision of utilities is very mission oriented in most air mobile or transportable shelters.

There are, however, some notable trends, discussed below, in air mobile shelter design that seem somewhat peculiar when compared to more conventional commercial-type prefabricated or portable buildings.

2.4.5.1 Floors

Floors for large tents and air-supported buildings and for large hangar structures such as the Bare Base hangar are typically not considered as part of the basic shelter set. For whatever reasons this might be, such as lack of mission need or excessive loads for lightweight construction, the effect on physical and cost evaluations is that this major shelter element is omitted from expansion ratio and cost comparisons with shelter concepts that include floors. Similarly, physical and cost comparisons of air transportable buildings with similar function USAF buildings as defined by AFM 88-2 (Reference 23) can be misleading.

2.4.5.2 Foundations or Supports

There are no notable exceptions in the large variety of mobile shelters reviewed that require field construction of foundations. Additionally, most rigid wall shelters, and many flexible-wall shelters are provided with easily-adjustable base plates and/or support jacks that accommodate variations in ground elevation of up to 1-1/2 feet along the longest shelter dimension. Tie-down anchors for supplementary stabilization are commonly provided. Reported field experience (see References 6 through 22) almost universally has been less than completely satisfactory; ground subsidence and/or original levelness has typically required blocking and/or continuous adjustment. Additionally, load introduction into floors or other parts of the shelter has caused damaging "racking" loads.

2.4.5.3 Windows, Doors, and Vents

Compared to conventional prefabricated buildings, current air mobile shelters generally have fewer and smaller windows, doors, and vents. While fabrication efficiency has probably benefited from this approach, utility has suffered (References 6 through 22). Full advantage is not taken of natural ventilation and natural light.

2.4.5.4 Interior Space Planning

Except for hangar-type portable shelters, there is little evidence in the literature that the internal space and/or subdivision of that space in current shelters is configured primarily by mission requirements.

A common apparent reason for the deployed internal dimensions of most rigid wall shelters is the nominal headroom requirement and the specific stowed dimensions required by the shipping method. The expansion ratio possible within these constraints then determines the deployed dimensions.

No notable examples were found in current mobile shelters of design features specifically included for acoustic control, optimum lighting placement, privacy, and flexibility of wall mounting provisions.

Blackout provisions are commonly provided, however. References 6 through 30, however, cite many shortcomings in this area, such as no light plenums around doors, requiring lights to be shut off for entry or exit.

2.4.5.5 Provision of Basic Utilities

Most mobile shelters, except for tents, have basic provisions for hookup to electrical power, water, and air conditioning. Many shelters come with heater kits, air conditioning sets, lighting sets, and power outlet kits, or these provisions are built in.

Most comments in the literature on utilities can be characterized as criticism of provided capacity or reliability, rather than conceptual criticism.

No portable shelter examples were located, military or commercial, that use solar heating, heat pumps, skylights, variable or selectable coatings, automatic-darkening windows, heat-controlled awnings, and other supplements to lighting and environmental-control subsystems that are in use in commercial buildings.

2.4.5.6 Shipping and Storage Configurations

Compatibility in the shipping mode with one or more "systems" was a basic design input to all shelters reviewed. The most common systems were:

1. ISO standards, as defined by Reference 27
2. USAF system 463L, including mobilizers
3. MH-5 helicopter lift.

The references reviewed did not indicate any examples or opinions that any shelter category was basically incompatible with any mode of shipping. Instead, compatibility or incompatibility was a design choice. As a matter of fact, the conclusion regarding the many transit-related problems cited is that inappropriate material selection and design execution on the detail level accounts for the high frequency of minor damage and handling difficulties. For example, interface clearances and other provisions for handling equipment often were not adequate; materials for handling fittings were not strong or durable enough.

In all cases of shelters, when installed mission equipment is subtracted, weight was not a difficult design goal, but "cube" was. Even with installed equipment (continer mode), "cube" was almost always the significant design limit.

2.4.5.7 EMI Isolation

No examples of flexible wall shelters were found that had special provision for EMI isolation.

In general, only the small, rigid wall shelters had provision for the necessary gaskets, aluminum steel panels, copper screens, filters on wiring feed-throughs, etc., that represent current practice in EMI shielding (Reference 27). Basic EMI control measures consist of:

1. Overall shelter shielding with ferrous or nonferrous sheet
2. Filtering of all wire penetrations
3. Suppression of interior fluorescent lighting

2.4.5.8 Maintenance and Repair

Current mobile shelters can be classified as having one common characteristic regarding provisions for damage repair: The factory-built shelters require factory-type equipment and skills for most repairs. In this sense, the current shelters are not different from some military-service hardware, but are very different from conventional field-fabricated wood, masonry, and steel buildings.

This explains why the data reviewed (see References section of this report) reported many instances of "expedient"-type repairs, such as patches of dissimilar materials; riveting to replace bond failures; lead filler to fill dents; supplementary bracing or doublers on bent or buckled beams instead of replacement; rerouted wiring or plumbing rather than replacement, etc.

While military skill levels seem to adequately support this type of repair, many repairs of this type can tend to decrease or prevent striking, stowage, storage and successful redeployment, especially with expandable shelters.

A review of the field service reports (see References) as regards painting, cleaning, inspection, lubrication, adjustment, and similar routine maintenance requirements and procedures, generally evaluates most current shelters as being at the superior end of today's state of the art on basic material selection and design approach. Accessibility and simplicity are generally very good. The large majority of field failures are concentrated in the area of detail design deficiencies related to severe environment or hard usage, rather than lack of provision for routine maintenance.

2.4.5.9 Deployment and Erection

The data reviewed on current shelters generally indicates that stowing, onloading, offloading and deployment of all current shelters were not negatively constrained by any basic feature of any shelter classification shown on Figure 1. Most shelters reviewed are not multi-modal (i.e.; ISO and 463L requirements), but no concept seems unable to be designed for such a requirement. In fact, several shelters now available or in development have this feature, as well as built-in provisions for forklift and ground-skid capability (see References 29 through 32).

Erection simplicity and speed have been a basic design goal of all current shelters; the literature reviewed and the field observations made during Phase I confirm that (1) this general goal has been achieved, and (2) specific crew-size/time goals for each design have been achieved.

2.5 CURRENT SHELTER OPERATIONAL APPROACHES

References (2), (4), (15), (24) and the Request for Proposal for this Study discuss the concepts of disposable shelters and short-term versus long-term designs, in the sense of durability when deployed.

Except for the work described in Reference (24) on foam-in-place disposable shelters, no current examples of disposable military shelters were located. Several private individuals have constructed foam-in-place residences, with living quarters being cut with a sabresaw out of a hemispheric "blob" of polyurethane foam. Easy portability and rapid deployment, however, were not goals of these experiments.

The concept of short-term deployment, or "expeditionary" deployment, is not usefully defined in shelter terms in the references cited. However, the limited life of tents noted in Reference (2) puts these shelter types in the short-term deployment category, by default. The amenities provided with most tents, and their intrinsically good portability is also consistent with this classification.

SECTION III
PERFORMANCE AND EVALUATION CRITERIA FOR ADVANCED CONCEPTS

3.1 INTRODUCTION

Section II of this report presented the results of the Air Mobility Shelter Conceptual Study Phase I, general review of current shelters. The overall review consisted of:

1. Identifying and acquiring data on a very comprehensive range of air-mobile shelters and other shelters similar in physical or functional concept.
2. Classifying the shelters as to common features and unique features, both on the conceptual level, and on a detail level.
3. Identifying general and detail performance criteria for shelters.

The overall conclusion was that despite the large variety of shelter concepts that are available, the detail design approaches are remarkably limited as regards structure design and material selection.

As a result of this review, it is concluded that existing shelters should be rated in two ways:

1. Ability of a shelter concept to meet general requirements, regardless of whether or not a specific shelter is currently capable of meeting detail requirements.
2. Specific, recurring detail performance shortcomings of one or more existing shelter concepts that indicate areas that should be emphasized in the development of advanced concepts.

The above-listed shelter concept ratings are presented in this section. Following this evaluation, specific design goals are identified and target values are recommended. This evolutionary approach to developing advanced shelter concepts, schematically shown in Figure 2, is consistent with the two major findings of the Phase I shelter review:

1. A rigorous definition, classification, and screening of existing shelters and shelter concepts proposed fails to identify any basic untried approaches.
2. The major shortcomings of current shelters are not flaws in concept, but rather a function of inadequate details of design and/or a materials limitation.

Therefore, material substitution in current concepts should make a basic contribution to improved shelter performance in all aspects.

3.2 GENERAL PERFORMANCE AND EVALUATION CRITERIA FOR SHELTER CONCEPTS

In the process of examining current shelters, a large number of performance and evaluation criteria were identified in the References. In this

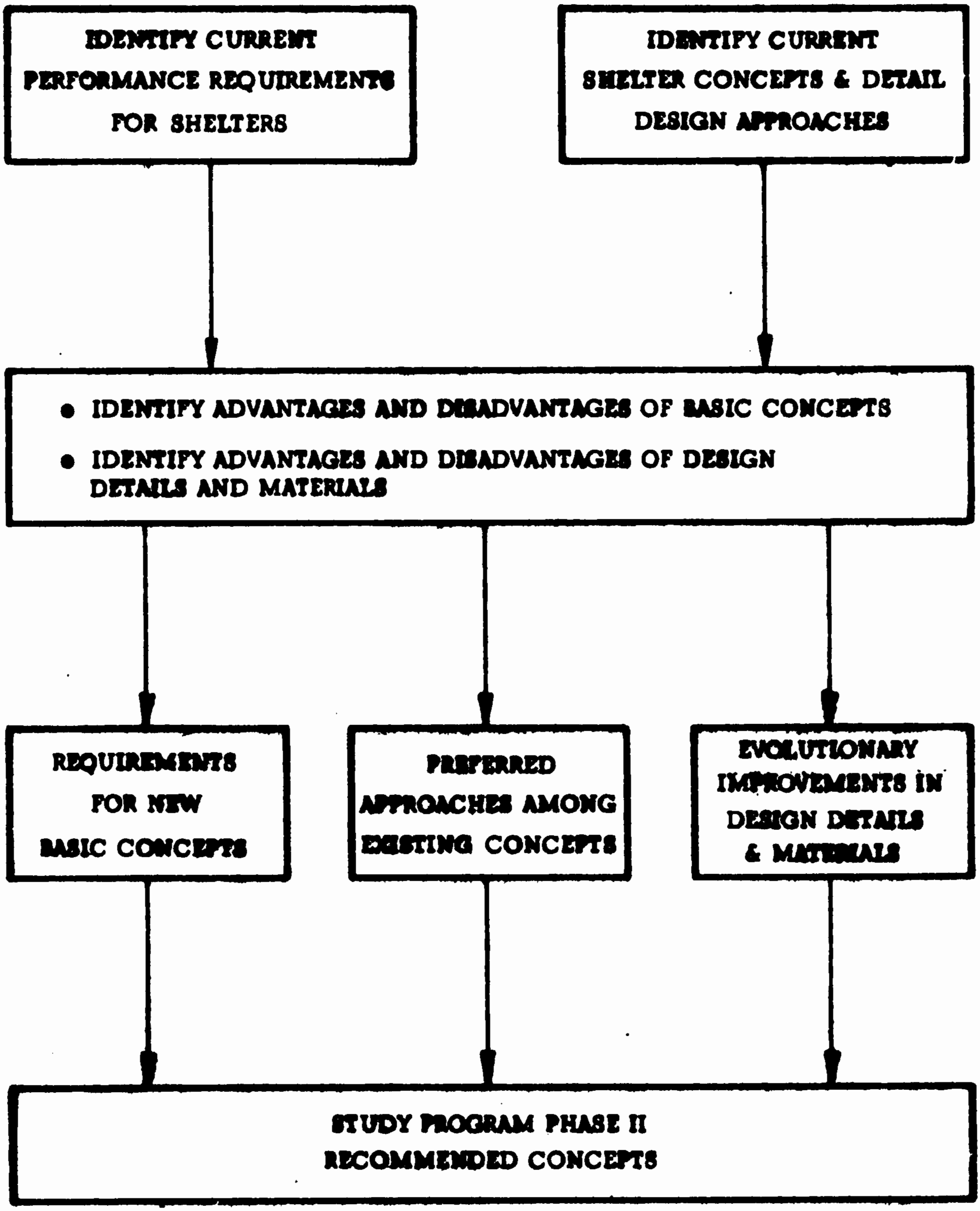


Figure 2. Evolution of Advanced Shelter Concepts

report, for the purpose of concept evaluation, criteria and requirements are separated into two categories:

1. General, unquantified
2. Specific, quantified.

Table 4 is an aggregation of the majority of suggested general shelter requirements, in the literature, and typical individual or groups of related specific detail requirements. The table draws heavily on References 17 and 27, which are notable for being excellent examples of systematic analysis and presentation of general shelter requirements. The detail requirements of Table 4 also reflect the specific requirements of the Air Mobility Shelter Conceptual Study Statement of Work. Table 4 requirements at this point are neither ranked nor weighted. In addition, overlapping of requirements is present in the interest of being relatively inclusive. Detail data is presented as nominal values only; for example, ISO container dimensions are stated as 8 by 8 by 20 feet, rather than the actual dimension.

3.3 EVALUATION OF BASIC CONCEPTS

The ability of current shelter concepts to meet the general requirements and criteria of Table 4 was examined. The intent of this evaluation was to highlight concepts which offer a good basic starting point for advanced concepts using the materials of the 1980 time frame. The unweighted evaluation on each criteria was based on demonstrated and reported performance of existing shelters and on experienced judgment as to basic concept capability limits or advantages, with today's materials, independently of whether or not a design actually met a performance goal.

For example, a current tent would not be penalized for inability to support a heavy snow load since the tent could have been designed to meet that requirement. The evaluation of current shelter concepts is presented in Table 5. The evaluation criteria are from Table 4. Shelter categories rated are those shown in Figure 1.

The rating code in Table 5 is defined as follows:

Rating Value	Rating Definition
5	Superior in concept and good demonstrated field experience.
4	Superior in concept and some demonstrated field experience.
3	Good concept but not used to maximum potential due to material limitations.
2	Relatively poor concept and/or poor demonstrated field experience.
1	Poor or unworkable concept or not applicable.

TABLE 4. GENERAL AND SPECIFIC SHELTER REQUIREMENTS

GENERAL REQUIREMENT		TYPICAL SPECIFIC CRITERIA
R-1:	High Expansion Ratio from Stowed to Deployed	• Deployed volume/stowed volume • Deployed area/stowed volume • Deployed area/deployed volume • Deployed base area/stowed base area • Deployed volume/deployed surface area • Deployed base area/deployed surface area
R-2:	Lightweight	• Stowed density, lbs/cu ft • Weight per unit deployed base area • Weight, absolute • Weight per unit deployed volume • Weight per unit stowed base area (with payload or without payload)
R-3:	Adaptable to Diverse Uses	• Deployed height and/or width • Storage volume and dimensions when stowed • Floor load capability • Compatible with mounting provisions of modification kits • Modular designs • Commonality among shelters • Provisions for installing mission equipment • Basic utility provisions defined

TABLE 4. GENERAL AND SPECIFIC SHELTER REQUIREMENTS (CONTINUED)

GENERAL REQUIREMENT	TYPICAL SPECIFIC CRITERIA
R-4: Simple and Rapid Erection and Knockdown	• Maximized use of captive or monolithic components • Maximum crew size allowable • Maximum erection time allowable • Minimum crew size • Skill level of crew • No special tools required • No power tools required • Tools captive and/or with kit
R-5: Redeployable and Long Service Life (in Storage and Deployed)	• Total useful life, deployed, with only routine maintenance • Redeployments planned during service life • Total storage life, with only routine maintenance
R-6: Durable and Damage-Resistant	• Only cleaning, painting, adjustment checks, and lubrication required, deployed or stored • Minimum use of consumable items • Meets maintainability and reparability general requirement • Meets environmental general requirement
R-7: Easily Maintained and Repaired	• Only standard tools required • Tools captive to shelter and/or part of shelter kit • Skill level of crew • Placard instructions preferred; technical manuals required • No interruption of mission use during maintenance or repair • Spares, consumables, kit with shelter

TABLE 4. GENERAL AND SPECIFIC SHELTER REQUIREMENTS (CONTINUED)

GENERAL REQUIREMENT		TYPICAL SPECIFIC CRITERIA
R-8:	Esthetics and Physical Amenities Conducive to Efficiency	• Interior light levels • Internal sound damping • Partitions for privacy • Internal color scheme
R-9:	Safety Engineered	• Noncombustible and nontoxic materials • Non-slip floors • "Building-code" type stairway rise, wiring, and plumbing requirements • See-through panels on doors • Non-protruding door handles and other permanent fittings • Tool required for access to adjustment points and utilities • All mission and load requirements equal or better than personnel load requirements
R-10:	Air-transportable and also Compatible with Other Shipping/Handling Systems	• Compatible with 463L system • Compatible with ISO standards • Can be skidded by vehicle • C.G. and lift-points compatible with helicopter lift • Fork-lift provisions
R-11:	Capability for Defensive Provisions	• Blackout capability • Inherent chemical/biological protective capability • Capability of passive defense • EMI control capability

TABLE 4. GENERAL AND SPECIFIC SHELTER REQUIREMENTS (CONTINUED)

GENERAL REQUIREMENT	TYPICAL SPECIFIC CRITERIA
R-12: Can Operate in Severe Range of Operating Requirements	• Provision for climate kits • No site preparation required • Load, shock, and vibration standards • Air temperature range • Solar load • Humidity, maximum • Snow loads • Wind loads • Altitude, deployed • Altitude, air shipment • Rainfall • Salt fog • Complete shelter • U-factor
R-13: Material Selection and/or Structural Element Selection	• Corrosion resistant • Fungus resistant • Resistant to vectors • Nonmetallic • Nonconductive • Fire resistant • Nontoxic • Low thermal conductivity • High specific strength and stiffness • Fracture and creep resistant • Abrasion resistant • UV resistant • Impermeable to fluids and gas • Stable properties with temperature changes

TABLE 4. GENERAL AND SPECIFIC SHELTER REQUIREMENTS (CONCLUDED)

GENERAL REQUIREMENT	TYPICAL SPECIFIC CRITERIA
R-14: Energy Efficiency	• U-factor, entire shelter • Requirement for climate kits • Doors, windows, shades, vents engineered for maximum climate control capability • Solar control provisions • Independent or central air conditioning compatibility
R-15: Low Manufacturing Cost, with All Other General Requirements Met	• Maximum use of monolithic, machine-produced parts, and/or standard commercial parts • Maximum use of common panels, other elements, with a specific shelter • First cost per square foot of deployed shelter compared to equivalent-function AFM88-2 facility
R-16: Life-cycle cost minimized, understated deployment scenario (Note: See subsection 3.5, Cost Factors, for further discussing of cost approaches)	• First cost per square foot of deployed shelter compared to equivalent-function AFM88-2 facility • Routine maintenance and average annual cost percentage of first cost, deployed or stowed • Annual utility costs equal or better than costs for AFM 88-2 type buildings, on a per square foot basis • Sum of present value of shelter first cost, annual maintenance and operating costs, and programmed deployment costs, less estimated salvage value, equal or less than same costs for permanent AFM88-2 type buildings

TABLE 5. EVALUATION OF CURRENT SHELTERS AND CONCEPTS

GENERAL REQUIREMENT (See Table 4)	SHELTER TYPE: (See Figure 1) A. FRAMEWORK SUPPORTED - FLEXIBLE WALLS										
	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11
R-1	4	4	2	3	2	3	4	4	4	4	4
R-2	4	4	3	4	3	4	4	4	4	4	4
R-3	4	4	3	4	3	4	4	4	4	4	4
R-4	3	5	3	4	3	3	4	4	4	4	4
R-5	3	3	3	3	1	4	3	4	4	3	4
R-6	3	4	3	4	2	4	3	4	4	3	4
R-7	4	4	3	4	3	4	4	4	4	3	4
R-8	3	3	3	3	3	3	3	3	3	3	3
R-9	4	4	4	4	4	4	4	4	4	5	4
R-10	4	4	3	4	4	4	3	4	4	5	4
R-11	3	3	3	4	4	2	2	4	4	4	4
R-12	2	2	1	2	2	2	2	2	2	2	2
R-13	2	2	2	2	2	2	2	2	2	2	2
R-14	2	2	2	2	2	2	2	2	2	2	2
R-15	3	3	2	3	3	2	3	3	3	2	3
R-16	(No substantiated data found on life-cycle costs of current shelters)										
Total Rating	48	51	40	50	41	47	47	52	51	50	52
Average Rating	3.2	3.4	2.7	3.3	2.7	3.1	3.1	3.5	3.5	3.3	3.5

TABLE 5. EVALUATION OF CURRENT SHELTERS AND CONCEPTS (CONTINUED)

GENERAL REQUIREMENT (See Table 4)	SHELTER TYPE: (See Figure 1) B. AIR-SUPPORTED, PRESSURIZED INTERIOR - FLEXIBLE WALL										
	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10	B-11
R-1	3	5	3	4	3	4	4	3	3	3	4
R-2	4	4	3	4	3	4	4	4	4	4	4
R-3	3	3	2	3	2	3	4	4	3	4	4
R-4	2	5	1	4	3	3	4	4	4	3	4
R-5	2	2	2	2	1	2	2	2	2	2	2
R-6	2	2	2	1	1	2	2	2	2	2	2
R-7	3	3	2	3	3	3	3	3	3	2	3
R-8	3	3	3	3	3	3	3	3	3	3	3
R-9	4	4	4	4	4	4	4	4	4	5	4
R-10	3	3	3	3	3	3	3	3	3	4	3
R-11	3	3	2	3	3	3	3	3	3	3	3
R-12	2	2	1	2	2	2	2	2	2	2	2
R-13	2	2	2	2	2	2	2	2	2	2	2
R-14	2	2	2	2	2	2	2	2	2	2	2
R-15	2	2	2	2	1	2	2	2	2	2	2
R-16	(No substantiated data found on life-cycle costs of current shelters)										
Total Rating	40	45	34	42	36	42	44	43	42	43	44
Average Rating	2.7	3.0	2.3	2.8	2.4	2.8	2.9	2.9	2.8	2.9	2.9

TABLE 5. EVALUATION OF CURRENT SHELTERS AND CONCEPTS (CONTINUED)

GENERAL REQUIREMENT (See Table 4)	SHELTER TYPE: (See Figure 1) C. AIR-SUPPORTED, PRESSURIZED WALL - FLEXIBLE WALL										
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11
R-1	3	4	3	3	3	3	3	4	4	4	4
R-2	4	4	3	4	3	4	4	4	4	4	4
R-3	4	4	3	4	4	4	4	4	4	4	4
R-4	3	4	1	3	3	3	3	3	3	3	4
R-5	2	2	2	2	2	1	2	2	2	2	2
R-6	3	4	3	4	2	4	3	4	4	3	4
R-7	4	4	3	4	3	4	4	4	4	3	4
R-8	3	3	3	3	3	3	3	3	3	3	3
R-9	4	4	4	4	4	4	4	4	4	5	4
R-10	3	3	3	3	3	3	3	3	3	3	3
R-11	4	4	3	4	4	4	4	4	4	4	4
R-12	3	3	1	3	3	3	3	3	3	3	3
R-13	2	2	2	2	2	2	2	2	2	2	2
R-14	3	3	3	3	3	3	3	3	3	3	3
R-15	2	2	2	2	1	2	2	2	2	2	2
R-16	(No substantiated data found on life-cycle costs of current shelters)										
Total Rating	47	50	40	48	42	48	47	49	49	48	50
Average Rating	3.1	3.3	2.7	3.2	2.8	3.2	3.1	3.3	3.3	3.2	3.3

TABLE 5. EVALUATION OF CURRENT SHELTERS AND CONCEPTS (CONTINUED)

GENERAL REQUIREMENT (See Table 4)	SHELTER TYPE: (See Figure 1) D. RIGID WALL, NON-EXPANDABLE										
	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	D-10	D-11
R-1	1	1	1	1	1	1	1	1	1	1	1
R-2	2	2	2	2	2	2	2	2	2	2	2
R-3	2	3	1	1	1	3	2	3	3	4	3
R-4	2	3	2	3	3	3	2	3	2	3	3
R-5	1	1	1	4	1	2	2	2	2	3	2
R-6	2	3	2	3	1	3	2	2	3	3	2
R-7	2	3	2	3	1	3	2	2	3	2	3
R-8	3	3	3	3	3	3	3	4	3	4	3
R-9	3	4	3	3	4	4	3	4	4	4	3
R-10	2	3	2	3	3	4	3	2	2	3	2
R-11	4	4	4	4	4	2	2	1	1	1	1
R-12	3	4	1	4	3	4	3	3	3	1	1
R-13	2	3	2	3	2	1	1	2	3	2	3
R-14	4	4	4	4	3	4	4	4	4	4	4
R-15	3	4	2	3	3	3	2	3	3	3	4
R-16	(No substantiated data found on life-cycle costs of current shelters)										
Total Rating	36	45	32	44	35	42	34	38	39	45	37
Average Rating	2.4	3.0	2.1	2.9	2.3	2.8	2.3	2.5	2.6	3.0	2.5

TABLE 5. EVALUATION OF CURRENT SHELTERS AND CONCEPTS (CONCLUDED)

GENERAL REQUIREMENT (See Table 4)	SHELTER TYPE: (See Figure 1) E. RIGID WALL, EXPANDABLE										
	E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8	E-9	E-10	E-11
R-1	4	3	3	1	1	3	4	4	2	3	3
R-2	3	4	3	3	2	4	4	3	4	4	4
R-3	4	3	3	3	2	1	1	4	2	3	3
R-4	3	4	2	3	3	1	1	3	2	4	3
R-5	3	4	3	4	1	4	2	3	4	3	4
R-6	4	4	3	4	3	4	3	1	1	1	1
R-7	4	3	4	4	2	1	1	1	1	2	3
R-8	4	4	4	4	3	1	1	1	1	1	1
R-9	3	4	3	3	4	3	2	3	4	3	2
R-10	3	4	2	1	1	4	2	1	1	1	1
R-11	1	1	1	1	1	1	1	1	1	1	1
R-12	3	4	1	3	2	3	2	3	4	1	1
R-13	2	3	2	3	2	3	2	1	2	3	4
R-14	3	4	3	1	1	1	1	3	1	1	1
R-15	3	4	2	2	3	3	3	3	2	3	4
R-16	(Nc substantiated data found on life-cycle costs on current shelters)										
Total Rating	47	53	39	40	31	37	30	35	32	24	36
Average Rating	3.1	3.5	2.6	2.7	2.1	2.5	2.0	2.3	2.1	2.3	2.4

3.4 EFFECTS OF EVALUATION ON ADVANCED CONCEPT DEVELOPMENT

A review of Table 5 indicates that an evaluation of concepts based on an equal combination of (1) basic ability of concept, and (2) current realization of potential, tends to indicate the following direction for advanced concept development:

1. All current concepts, with the exception of field-fabricated concepts and disposable concepts, appear to offer approximately equal potential for further development, based on basic and realized potential.
2. There are several recurring relative shortcomings in evaluated concept ability that indicate specific high-payoff targets for application of advanced materials.

Item No. 1 conclusion is highlighted by graphically displaying the unweighted <u>rating total</u> for each concept type in bar chart form, see Figure 3.

An analysis of Item No. 2 conclusion is presented in Table 6. The 16 general shelter requirements of Table 4 are listed along with the most common or prominent related detail design or material-selection problems that caused downrating of individual concepts.

3.5 WEIGHTED EVALUATION CRITERIA AND OVERALL DESIGN GOALS FOR ADVANCED SHELTERS

It is suggested that a rational final selection of shelter concepts that should be carried forward into preliminary design should be based on a weighting of the <u>relative</u> importance of each of the 16 basic, general shelter evaluation criteria of Table 4. This approach will aid in the decision of whether or not to reject a concept because of anticipated relative difficulty in meeting a specific physical requirement.

For example, the difficulty of "shelter/container" concepts in achieving "high expansion ratios" would be downgraded if the design-goal expansion ratio was a relatively low percentage of the total rating score. Conversely, if a concept such as a tent (1) could not easily be construed as being capable with advanced structural concepts of meeting snow and wind load requirements, (2) was scored low in this account, and (3) this requirement was weighted high, weighting system would tend to eliminate the tent on the basis of this most critical requirement.

Table 7 repeats the shelter general evaluation criteria of Table 4 and also lists the selected specific criteria suggested as the model or target criteria for advanced shelters. In cases where a range of performance is acceptable, the range is indicated. Then, the table puts a weighting factor on various points in the performance range. If a single-point criteria is stated, and a shelter cannot achieve that value, the score would be zero.

The weightings reflect the study conclusions regarding the relative importance of each criteria, as based on the review of the limitations of current shelters. The selected criteria values are generally comparable to the current achievement levels of Bare Base equipment, and in no case exceed

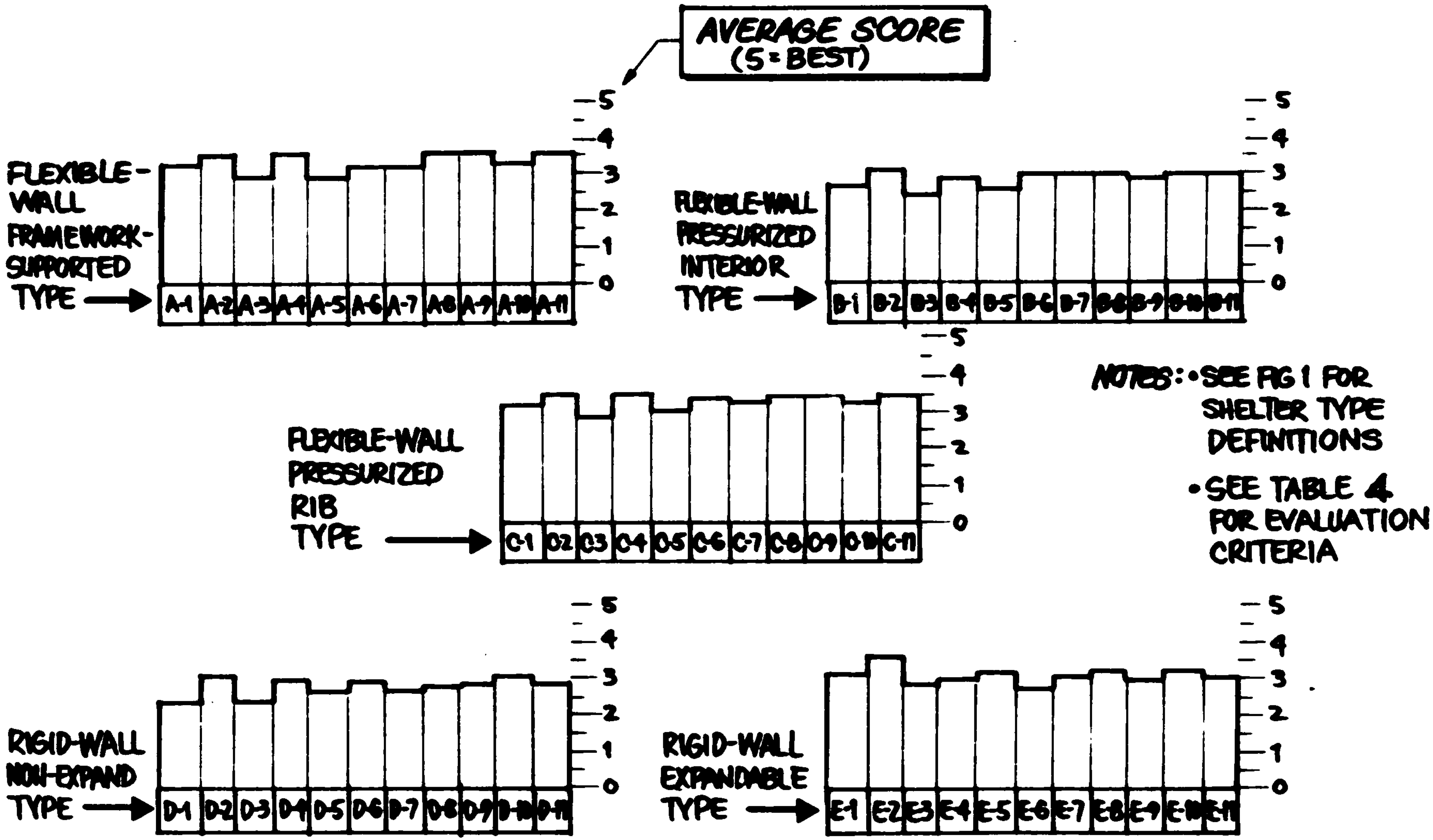


Figure 3. Concept Evaluation Average Scores

TABLE 6. RECURRING AND COMMON PROBLEMS WITH EXISTING SHELTER CONCEPTS

GENERAL REQUIREMENT (See Table 4)		RECURRING OR COMMON PROBLEM, ALL CURRENT SHELTERS
R-1:	High Expansion Ratio	• Only non-expandable rigid wall shelters have any basic limits or problems, due to mission requirements, such as storage or aircraft hangaring • All current or proposed aircraft can be accommodated with other concepts
R-2:	Lightweight	• No recurring problems; in fact, most stowed shelters are cube-limited
R-3:	Adaptable to Diverse Uses	• No basic limitations on any concept's ability to meet this requirement except as noted for Requirement R-1 • Current limits are primarily due to design goals specified for shelter • Lack of floors in larger shelters is only current notable shortcoming
R-4:	Simple and Rapid Erection and Knockdown	• No major recurring problem noted • Site level determination, anchoring, differential expansion, and dirt in mating parts • Missing tools is a minor but common recurring problem
R-5:	Redeployable and Long Service Life	• No common difficulties with any shelters as regards redeployment • Service life of current shelters within planning-purpose maintenance targets appears generally to be unachievable with any current shelter, due to durability problems (see R-6)

TABLE 6. RECURRING AND COMMON PROBLEMS WITH EXISTING SHELTER CONCEPTS (CONTINUED)

GENERAL REQUIREMENT (See Table 4)	RECURRING OR COMMON PROBLEM, ALL CURRENT SHELTERS
R-6: Durable and Damage Resistant	• Delaminations in bonded structures and adhesive joints from wracking load, bad bonds, differential expansion, and aging • Frequent dents and rips in skins and fabrics from handling • Water ingress or condensation internal to structure, especially in sandwich panels • Degradation (rips and general disintegration of nonmetallics, especially flashing and seals exposed to weather) • Structural failure due to shelter racking during transit or settling while deployed
R-7: Easily Maintained and Repaired	• No currently completely satisfactory method for detecting bond and water-ingress problems in sandwich panels • No easy method for field repairs, considering that normal patches and rivets can interfere with functions such as stowing and shipping • Normal settling is often beyond capability of leveling jacks; hoisting and blocking is required
R-8: Esthetics and Physical Amenities	• Generally insufficient organic or kit-provided lighting in larger shelters • Insufficient use of windows for lighting • Generally no provision for partitions for privacy, functional control, or acoustic control • Sound damping poor in all size shelter concept tents
R-9: Safety-Engineered	• Very good general design in almost all shelters • Some indications of desires for external lights • Inter-shelter wiring laying on ground has caused some problems

TABLE 6. RECURRING AND COMMON PROBLEMS WITH EXISTING SHELTER CONCEPTS (CONTINUED)

GENERAL REQUIREMENTS (See Table 4)		RECURRING OR COMMON PROBLEMS WITH ALL CURRENT SHELTERS
R-10:	Air-transportable and also Compatible with Other Shipping/ Handling Modes	• No basic problems encountered with any multi-modal designs
R-11:	Capability for Defensive Provisions	• Inherent blast-resistance and penetration problem with all current flexible wall, reusable shelters • Some penetration resistance improvements are possible • EMI control with advanced fabrics seems feasible
R-12:	Can Operate in Severe Range of Operating Environments	• No floors in large shelters • Ground settling problems with jacks • Anchors not capable of installation and/or holding • Wind loads on large doors on hangars • Sealing and flashing material failures and malfunctions • Differential expansion of large parts • Brittle failures at low temperatures of metallics and nonmetallics • Water leakage is a common problem
R-13:	Material Selection	• Covered individually in other "requirements" problem analysis • Most problems are concentrated around durability or basic adequacy of nonmetallics, including adhesives; UV tolerance is a notable problem
R-14:	Energy Efficiency	• Good insulation • Bad weather sealing (see R-12) • No use of state-of-the-art light and ventilation control techniques • Limited use of solar-control and wind/water-control add-on kits

TABLE 6. RECURRING AND COMMON PROBLEMS WITH EXISTING SHELTER CONCEPTS (CONCLUDED)

GENERAL REQUIREMENTS (See Table 4)	RECURRING OR COMMON PROBLEMS WITH ALL CURRENT SHELTERS
R-15: Low Manufacturing Cost	• Further improvements possible by reducing hand labor required by current structural/material approaches, because of multitude of pieces and separate operations
R-16: Low Life Cycle Cost	• Because of diversity of shelter missions and deployment scenarios, no common problems can be identified

TABLE 7. WEIGHTED EVALUATION CRITERIA AND SPECIFIC REQUIREMENTS

GENERAL REQUIREMENT		SELECTED CRITERIA	WEIGHTING SCORE (Zero if not met)
R-1:	Expansion Ratio	• Deployed volume/stowed volume:	
		100	6
		50	5
		25	4
		15	3
		10	2
		5	1
		1	0
R-2:	Lightweight	• Weight per deployed covered area:	
		2.5 lb/sq ft	5
		5.0	4
		7.5	3
		8.0 , or more	0
R-3:	Adaptable to Diverse Uses	• Floor load capability meets mission requirement	10
		• Deployed dimensions meet mission requirement	10
R-4:	Simple and Rapid Erection and Knockdown	• Crew size per 100 square feet of deployed base area:	
		1.5	10
		2.0	1
		3.0, or over	0

TABLE 7. WEIGHTED EVALUATION CRITERIA AND SPECIFIC REQUIREMENTS (CONTINUED)

GENERAL REQUIREMENT	SELECTED CRITERIA	WEIGHTING SCORE (Zero if not met)
R-4 (Continued)	• Total erection time:	
	2 hours	4
	4	3
	8	2
	24	1
	• All captive tools	1
	• All captive components	2
R-5: Redeployable and Long-Life in Storage and Deployed	• Total continuous deployed useful life with routine maintenance:	
	10 years	10
	5	5
	4 , or less	0
	• Number of deployments without rehabilitation:	
	3	10
	2	5
	1	1
R-6: Durable and Damage Resistant	• Same as R-5, plus	
	• No consumable repair items necessary	1
R-7: Easily Maintained and Repaired	• All field-replaceable components	1
	• All captive tools	1
	• All spares and consumables pitted with shelter	1
	• Meets all requirements for manuals, placards, skill levels	1

TABLE 7. WEIGHTED EVALUATION CRITERIA AND SPECIFIC REQUIREMENTS (CONTINUED)

GENERAL REQUIREMENT		SELECTED CRITERIA	WEIGHTING SCORE (Zero if not met)
R-8:	Esthetics and Physical Amenities	• Interior light level requirements met for all missions	3
		• Sound, control, colors, partitions, features provided	2
R-9:	Safety Engineered	• All criteria noted on Table 4 are met	20
R-10:	Air-transportable and Compatible with Other Systems	• Integral features provide 463L, ISO compatibility	5
		• Supplementary pallets or containers required	3
R-11:	Capability for Defensive Provisions	• Integral capability for blackout, CB, and ballistic protection	5
		• Add-on kits required for defensive provisions	3
R-12:	Can Operate in Severe Range of Operating Requirements	• No climate kits required	2
		• No site preparation kits required	2
		• Meets all load and shock requirements	10
		• Meets all other environmental specifications noted in Section I	10
R-13:	Material Selection	• Meets all criteria of Table 4	20

TABLE 7. WEIGHTED EVALUATION CRITERIA AND SPECIFIC REQUIREMENTS (CONCLUDED)

GENERAL REQUIREMENT	SELECTION CRITERIA	WEIGHTING SCORE (Zero if not met)
R-14: Energy Efficiency	• U-factor (whole shelter)	
	0.25	5
	0.30	2
	0.40, or greater	0
	• No climate kit required	2
	• Compatible with central air conditioning or individual air conditioning	1
	• Contains solar heating or control and engineered windows, shades, and vents	2
R-15: Low first cost	• Expressed as a percentage of equivalent function AFM88-2 building; percentage dependent on transport and deployment scenario and other factors in life-cycle cost	10
R-16: Life-Cycle Cost	• Routine maintenance material and manpower costs equal or less than 20 percent of first cost	10
	(Note: The contribution of deployment and transport manpower and shipping costs to life cycle costs are included by means of the evaluation criteria in R-1, R-2, and R-4.)	

the target or achieved values for the best specific Bare Base shelter for that particular criteria. In other words, full realization of Bare Base goals is the recommendation for advanced air mobile shelters.

3.6 COST FACTORS

The review of current shelters regarding cost relative to performance included three major considerations:

1. What approach should be used to establish a goal for shelter first-cost?
2. What approach should be used to establish a goal for shelter life-cycle cost?
3. What are the major factors in shelter design that influence cost?

3.6.1 First Cost Goals

Figure 4 is an array of shelter cost per square foot ranges versus percent of shelters, and versus percent of inventory floor space. This data is based on basic data of Reference 27, with added data from References 2, 3, 4, and 5, While this cost array certainly does not cover all current shelters, and is not normalized for inflation or other qualifiers, several hundred shelter models are included in the data, and the array is sufficiently skewed toward the 0-10 dollars/square foot range to be indicative of a desirable first-cost goal for any future shelters.

References 23 and 47 were also screened and the planning factor cost per square foot of hangars, personnel billets, and maintenance shops similar to Bare Base mission requirements were determined (1974 dollars). The $10 per square foot mobile shelter cost target of Figure 4 is seen to be generally less than for equivalent AFM88-2 buildings.

It should be clearly understood that this first-cost goal is a shelter-family goal, not a specific-shelter goal. The data of Reference 27 shows that per square foot costs tend to rise for smaller shelters.

3.6.2 Life Cycle Costs

No data was located on life-cycle costs of current mobile shelters. Many of the references cite, however, the same general factors as impacting life-cycle costs:

1. Expansion ratio (affects transport costs).
2. Weight (affects transport costs).
3. Durability, maintainability, and repairability (affects repair costs).

Therefore, life-cycle cost goals are included in the shelter evaluations in Tables 5 and 6 within those factors listed above, in that a good score in any of those areas is a measure of lower life-cycle costs. In addition, a typical planning factor maintenance cost factor (i.e., from Reference 48) is also included in Table 6.

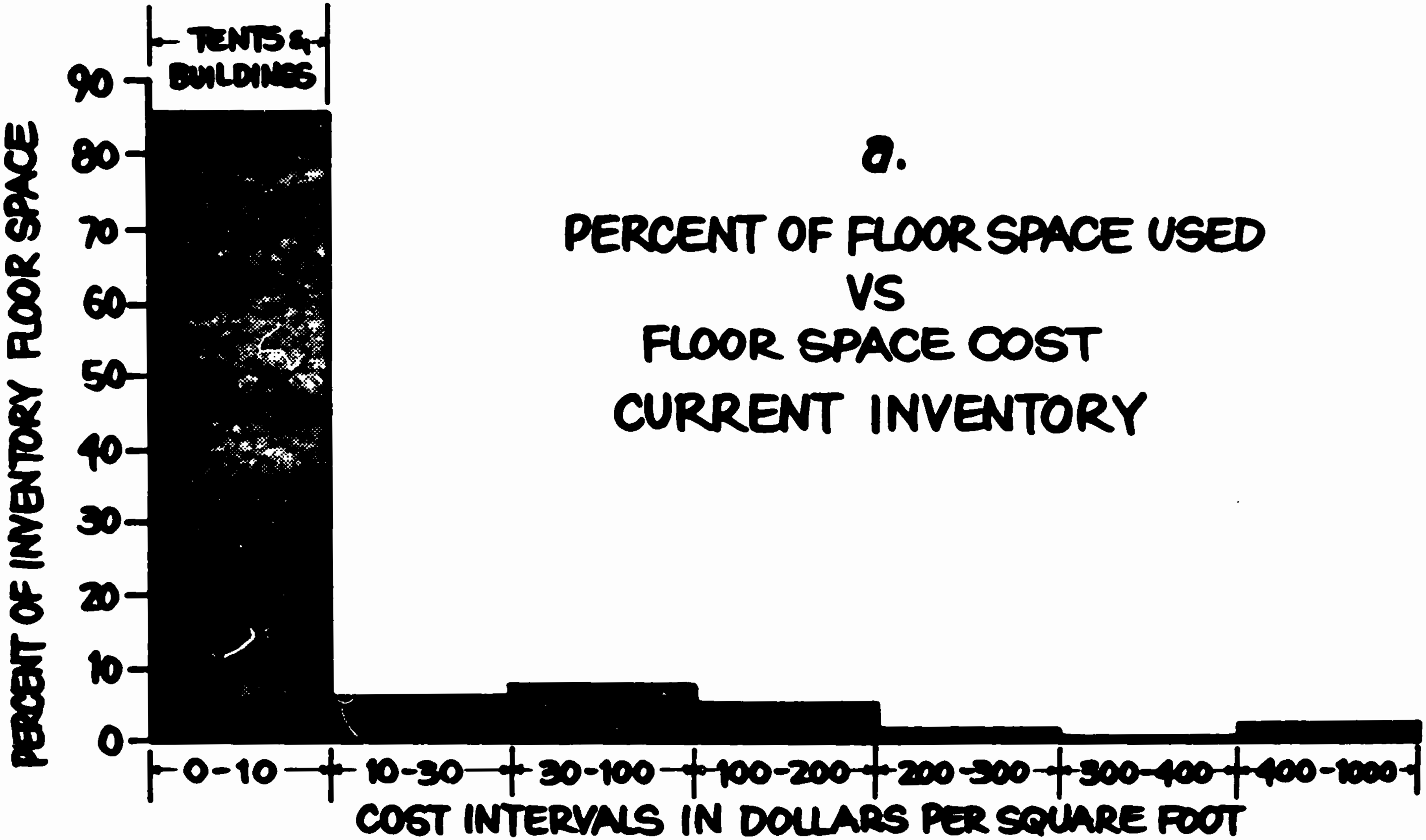


Figure 4. Shelter First Costs

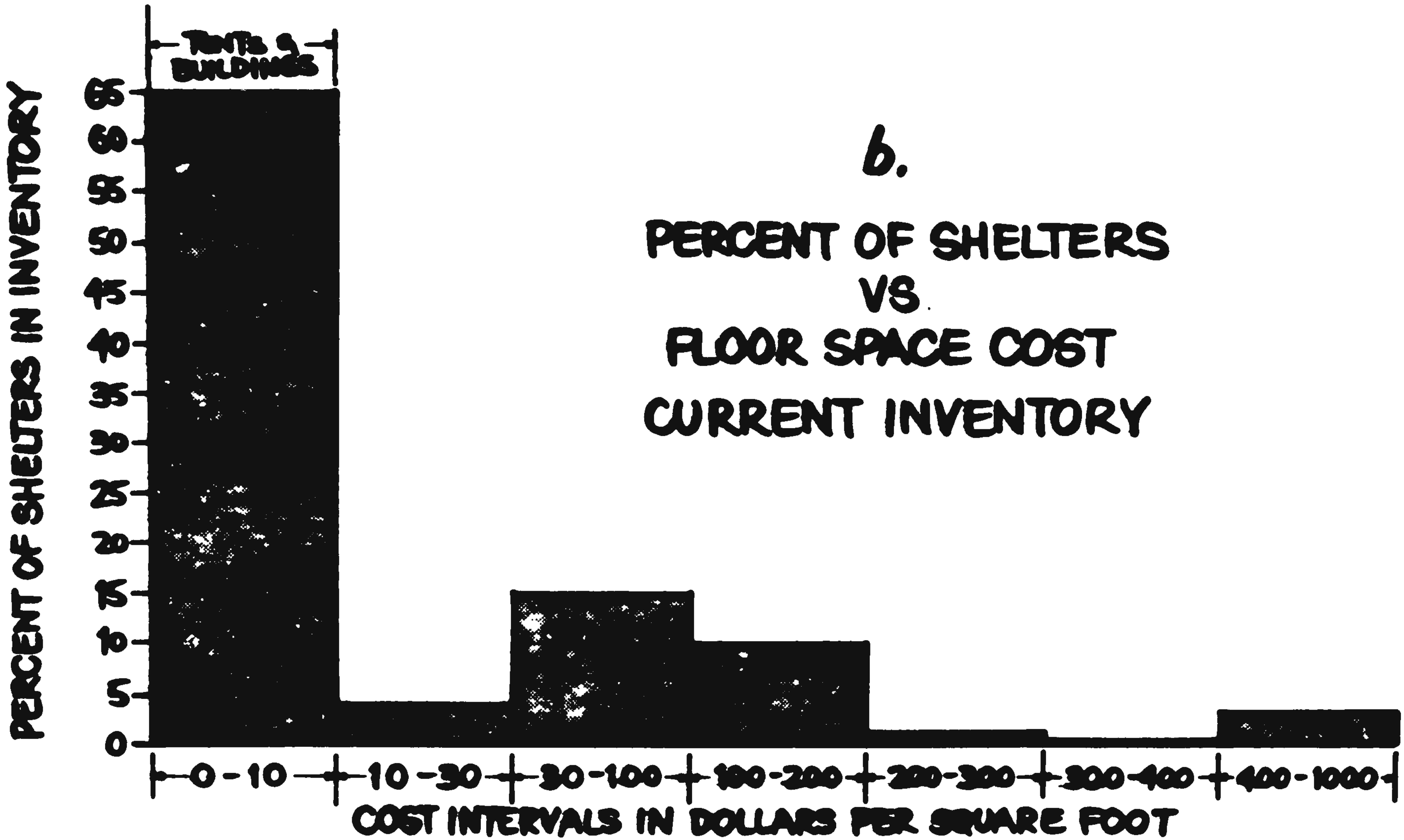


Figure 4. Shelter First Costs (Concluded)

3.6.3 Major Cost Factors

Figure 5 is a schematic illustration of the concept of the relative influence of first cost on life-cycle cost. While no data was located on mobile shelter life-cycle costs, Reference 48 and many similar construction-cost and building-operations-cost estimating manuals allocate life-cycle costs approximately as shown on the Figure. Figure 5 shows that first cost is less than one-half of life-cycle cost (typical for commercial buildings). Therefore, a premium material can often be used to lower routine maintenance and other operational costs, and also decrease the chance of unscheduled repair from damage. Because unscheduled repair from damage and lack of durability of materials were both recurring problems with most shelters reviewed, the use of premium materials should be considered in development of new shelters. By "premium," it is meant that a material is significantly higher in some basic property related to the function it must perform. Several examples are:

1. Nomex core, compared to paper core
2. Kevlar fiber, compared to fiberglass
3. Epoxy resin, relative to most thermoplastic resins.

Figure 5 also indicates the dramatic first-cost benefits, on a unit basis, by standardizing an assembly design, such as a panel. The data shown is for an 80-percent "improvement curve," which is typical for bonded sandwich structures (Reference 46).

As a specific example, if the use of a standard panel in a shelter set could increase the production run from 150 to 600, a unit cost reduction of 30 percent might be achieved by the "learning" benefits and opportunity to use more automated and efficient methods. Therefore, panel standardization is also an indicated high-payoff approach for future shelters.

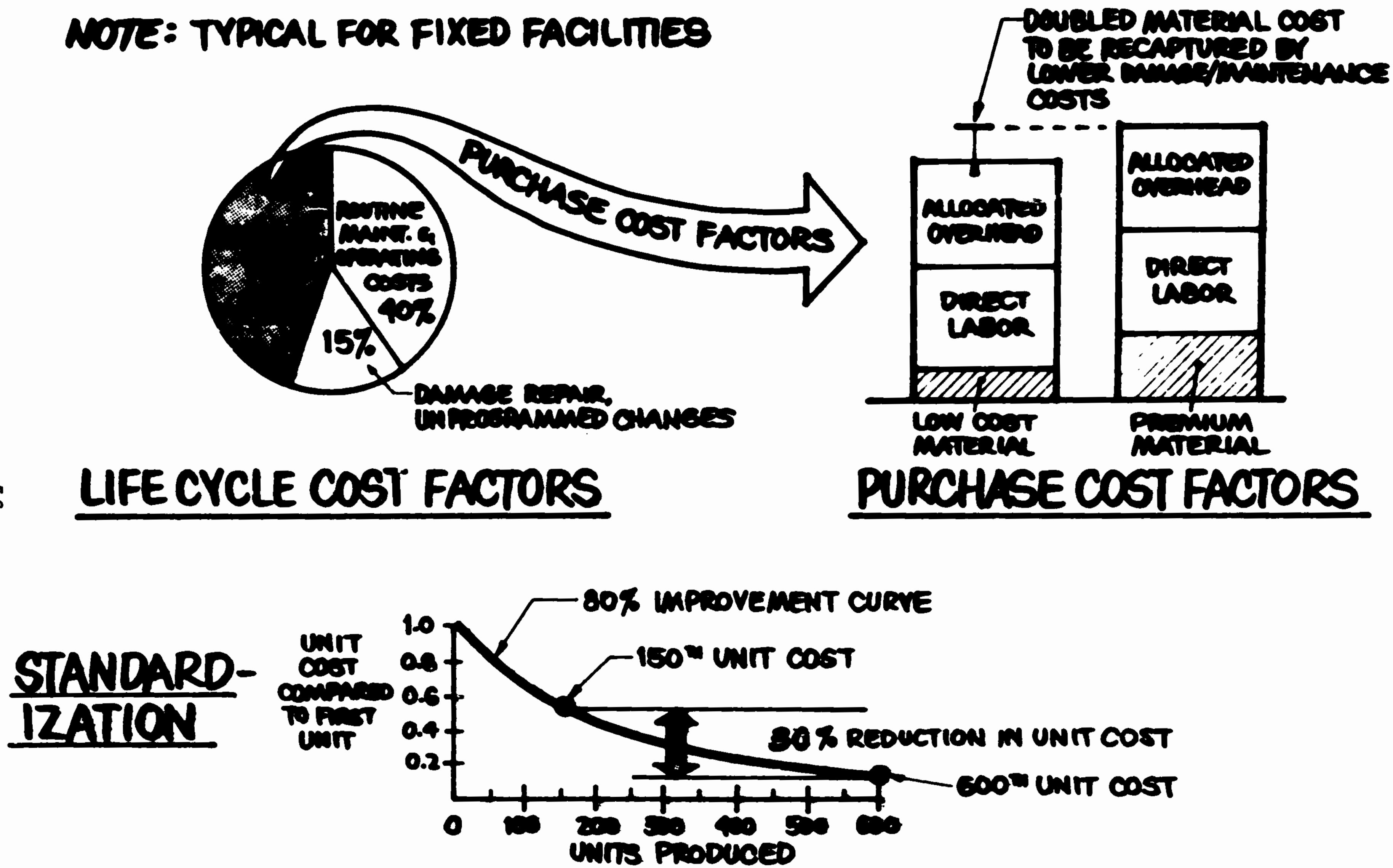


Figure 5. Major Shelter Cost Factors

SECTION IV
ELEMENTS OF ADVANCED CONCEPTS

4.1 INTRODUCTION

The review and analysis of current air mobile and other portable shelters presented in Sections II and III of this report suggest that existing basic shelter concepts already offer the basic potential to satisfy any desired requirement for expansion ratio, light weight, erection method simplicity, adaptability to diverse uses, service life, safety, compatibility with various transport systems, and relatively low first cost.

The shortcomings relative to permanent buildings in existing concepts are concentrated in the area of durability, repairability, environmental resistance, energy efficiency, and aesthetics/physical amenities.

This section presents the resulting recommendations for conceptual approaches to retain the demonstrated benefits of existing shelter concepts by evolutionary improvement of individual shelter system elements, by use of advanced, improved materials.

4.2 BASIC CONCEPTUAL APPROACHES

The basic recommended conceptual approach is comprised of the following features:

1. Shelter concepts, such as Bare Base-type shelters, LocArch, and flexible wall shelters of various types should be redeveloped with the addition of supplementary equipment, or kits, such as:
    a. Rapid-deployment foundation kits, including improved anchors and tie-downs.
    b. Rapid-deployment floor kits for hangar-size structures.
    c. Large-scale monolithic, complete-building weather-seal/thermal control flashing kits, either fabric or spray-on.
    d. Large-scale, complete-building EMI control cover kits, either fabric-based or spray-on.
    e. Container/pallet kits for multimodal transport.
2. Shelter concepts should provide for more extensive use of molded or otherwise formed, non-laminated sections, with stiffeners, hinges, other fittings, windows, vents, and other openings formed integrally with the production process; laminates would be used selectively for reinforcement of load-concentration points.
3. Shelter concepts should provide for improved damage resistance, ballistic penetration resistance, and durability in severe environments by:
    a. Use of premium-quality advanced materials (higher cost relative to other materials also meeting nominal load requirements).

   b. Use of increased section dimensions, coating thicknesses, additives, more-conservative safety factors, design allowables, and environmental-resistance assumptions.
4. The trend toward added weight implicit in Items 3a and 3b will be counteracted by the use of higher specific strength, high specific stiffness materials predicted to be available in the 1980's time frame.
5. The trend toward higher cost implicit in Items 3a and 3b will be counteracted by the increased use of automated manufacturing methods and inspection methods that prevent defective shelter elements from leaving the factory.
6. Shelter sizes should be chosen to allow the increased use of standard field-replaceable panels and other elements.
   a. Replaceability in the field of complete elements is the suggested approach to repairability and adaptability to special uses.
   b. The theoretical life-cycle cost penalty from the somewhat oversized shelters (for some missions) would be counteracted by the increased panel commonality.
7. Consideration should be given to the incorporation of special panels or separate modules for shelters that incorporate modern techniques of solar heat control and usage for air conditioning and lighting.

Figure 6 is a schematic presentation of the suggested approach to advanced shelter concepts. The balance of this report section presents a conceptual level discussion of each of the above individual-element approaches. In some instances, specific materials are mentioned for illustrative purposes. However, these specific material comments are not intended to be exclusive of other materials in the wide selection available. Section V presents a discussion of material alternatives.

4.3 SUPPLEMENTARY KIT CONCEPTS

The basic idea of supplementary kits presented here has three basic elements:

1. Experience with current shelter, and buildings in general, has shown that several traditionally needed building elements such as foundations, floors, and high-capability weather proofing are necessary in a significant percentage of locations.
2. Only smaller buildings can approach the goal of having built-in, universal provisions for these functions, with current and/or advanced materials.
3. Therefore, kits should be provided, in the amounts necessary to support the planned mission scenario (such as the ones currently being analyzed in the AFCEC study) (Reference 33.1) and deployed at the discretion of the base engineer.

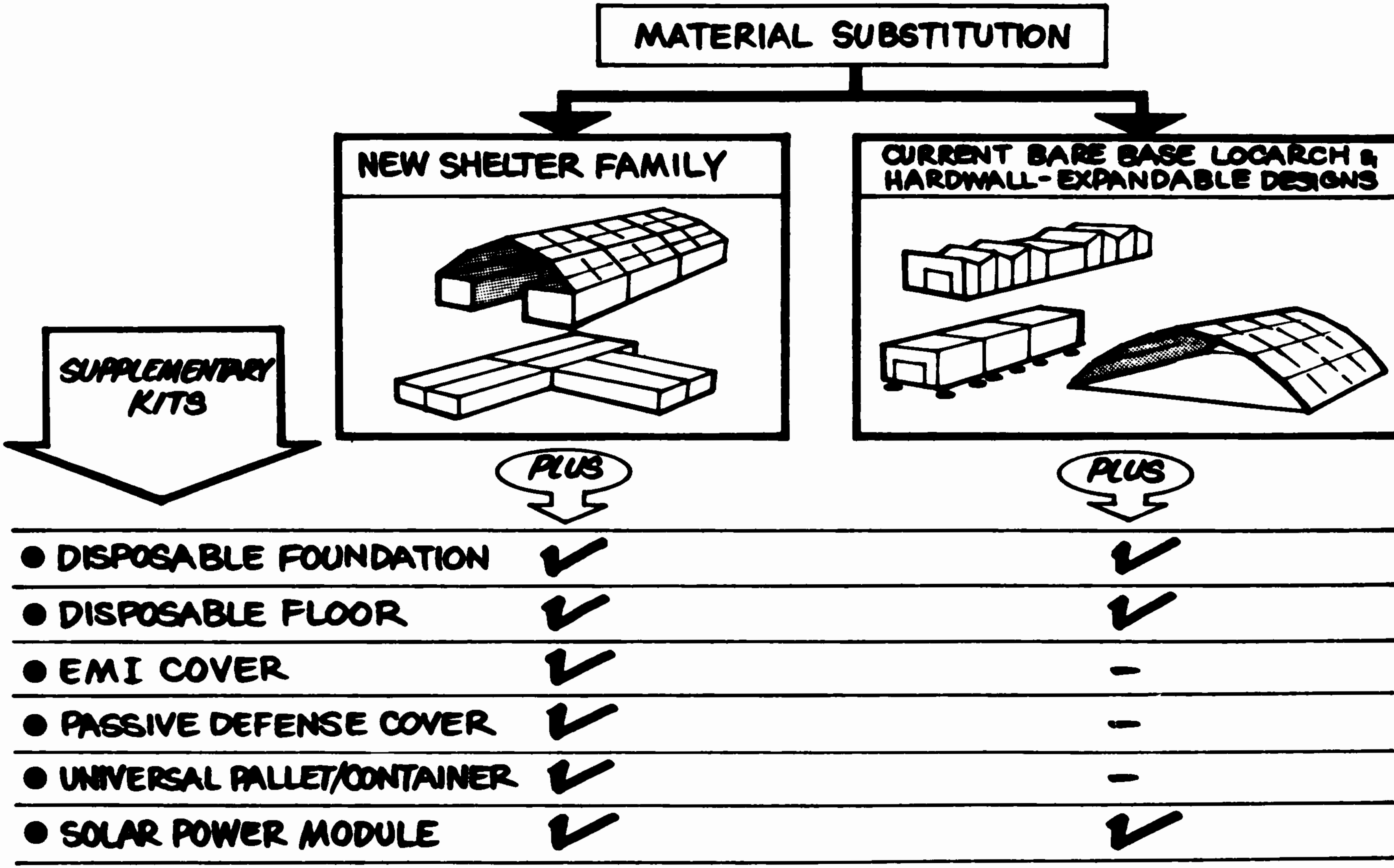


Figure 6. Advanced Shelter Concepts Overall Approach

Several kit concepts are presented in the following subsections.

4.3.1 Foundation Kit

The foundation kit requirement is for a low-shipping-volume, lightweight system that can rapidly produce foundation sections to supplement the load-distribution, ground isolation, and leveling capability provided with shelter leveling jacks, baseplates, and other adjustment features. An integral part of the kit would be a separate subsystem of anchors and anchor foundations.

The problem overcome with this kit would be the frequent shelter settling, water leakage through floors, and difficult leveling reported in the references. Elimination of these problems would also reduce related problems such as frame and fitting cracking, panel delaminations from moisture, and vectors, and would contribute to thermal control of shelter interior.

The key elements or parts of the kit are as follows:

1. Lightweight, impermeable, disposable membrane form, whose primary function is as a placement mold to develop foam-foundation density, with ground sealing as a secondary but not critical function; currently available hypalon-type fabrics would be suitable for this application.
2. Bottled, pressurized, two-component expanding foam system, with atomizing-type mixing, rather than mechanical mixing, foam could be polyurethane-type or epoxy-type.
3. Hand-wrenched foundation anchors (disposable), which can be driven right through the emplaced foamed foundation, and also be used as a supplemental anchor if guy wires are used with the shelter. Material could be steel or pultruded fiber-epoxy composite.
4. Possibly, an anchor-setting foaming epoxy injection kit.

The basis for forecasting successful development of a kit such as this is based on:

1. Recent Dow and Upjohn developments in field application of high-density polyurethane foams that do not require exact mixing proportions, which simplifies the foaming equipment and control skill requirements (References 34.1, 35.1 and 36.1).
2. Recent Bureau of Mines-sponsored research and testing on foaming-epoxy set disposable mine roof bolts (Reference 37).
3. U. S. Navy in-house study on foam-in-place landing mat (Reference 38).

Figure 7 is a schematic illustration of the foundation-kit concept.

4.3.2 Floor Kit

The floor kit requirement is for a disposable, low shipping volume, lightweight system that can rapidly produce a relatively low-quality, in terms of flatness, disposable floor, or at least a good ground sealer, for use in large hangar-type buildings. The kit function would be similar to that

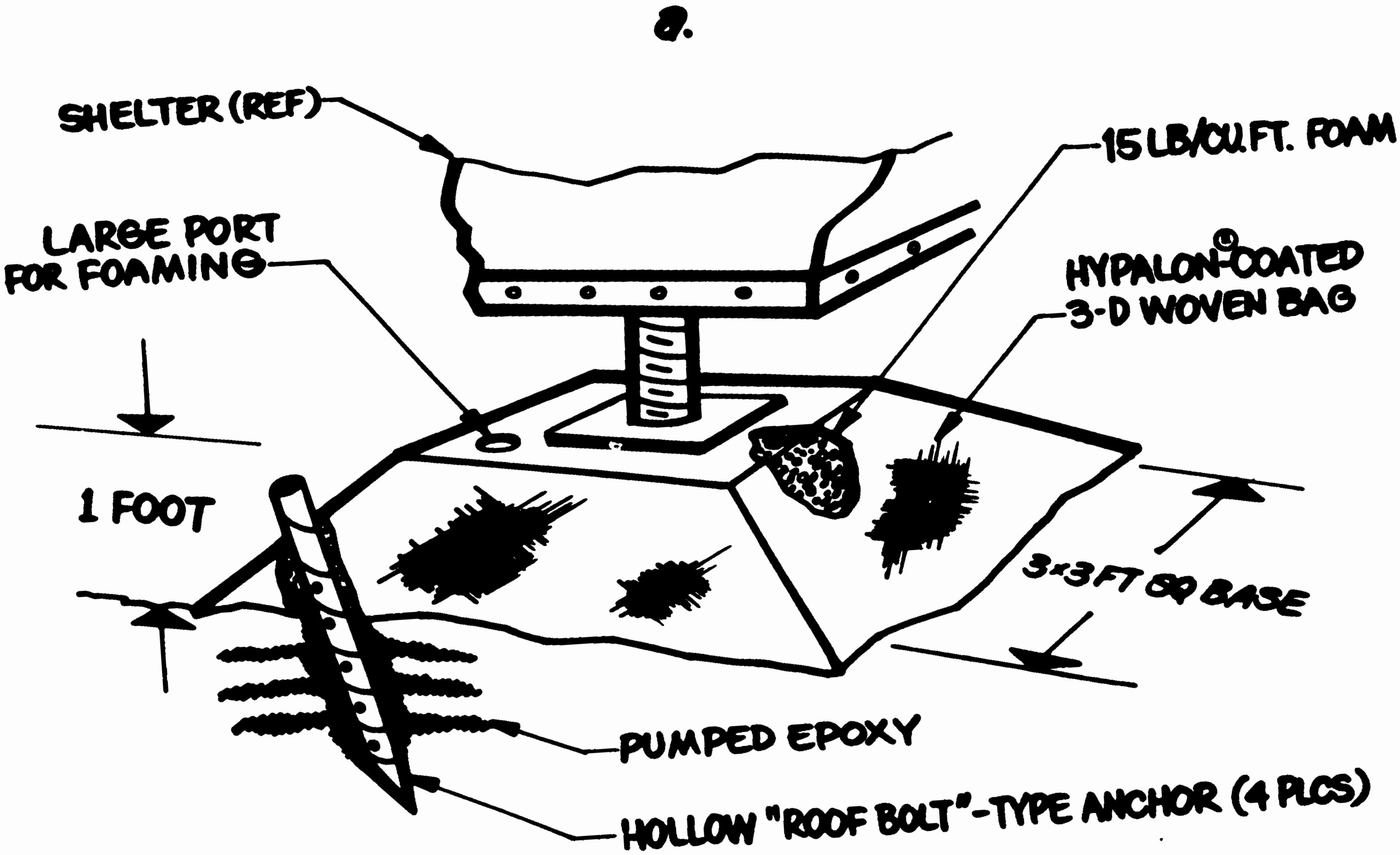


Figure 7. Foundation Kit Concept

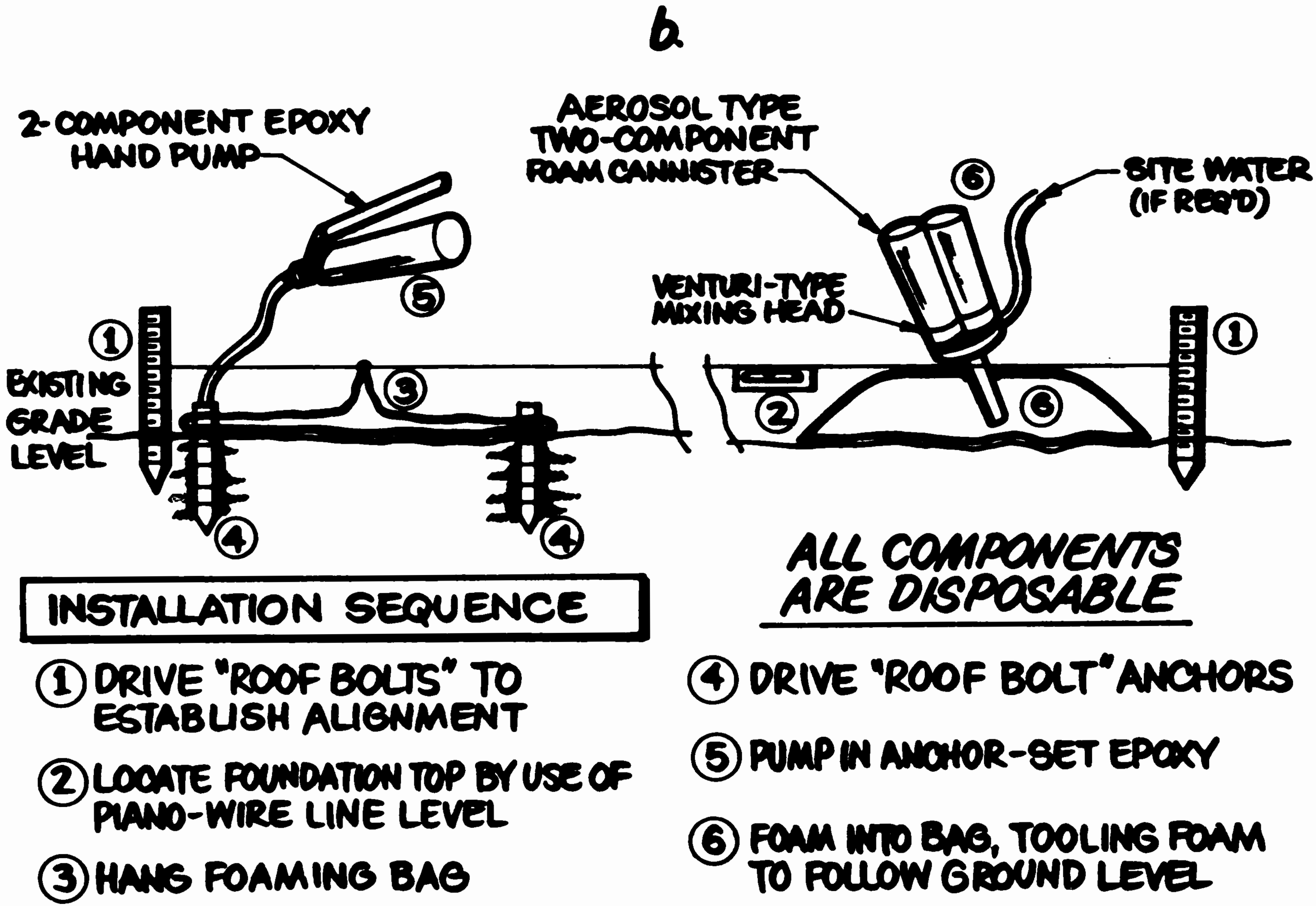


Figure 7. Foundation Kit Concept (Concluded)

proposed originally for the field-sprayed fiberglass mat for the Bare Base hangar (Reference 1). Load capability would be equivalent to expedient surface landing mat (References 39 and 40).

The problems overcome with this kit would be general cleanliness, overall floor level quality, isolation from ground moisture, and related secondary problems on shelter structure and stored equipment and/or airplanes.

The key elements of the kit are the same as for the foundation kit described in Subsection 4.3.1, as is the basis for forecasted successful development. Figure 8 is a schematic illustration of the floor kit concept. Note that several alternate installation concepts are presented. The "separate layup" concepts would probably produce structurally-superior floors because of the bonding process occurring between core and face sheets. However, based on current shortcomings of this approach in panels, coupled with operator skill requirements, the foam-in-bag is the preferred approach. This approach may also be amenable to application of current work (Reference 41) in woven "3-D" structures, if film-type material was inadequate. Typical materials would be fiberglass fabric bags and polyurethane foam core. So-called toxicity problems and fire-retardancy limits are essentially eliminated even with currently-available materials (Reference 36).

Both the foundation-kit concept and floor-kit concept offer the added "backup" potential to be used with indigenous materials such as sandbags.

4.3.3 Weather Kits

The subject of weather-sealing and insulating buildings is a major and continuing subject of study and experimentation in conventional buildings. The problem, never perfectly solved, is made more complex in current air mobile shelters in several respects:

1. Field erection with separable or hinged components inevitably results in misalignments of mating parts, beyond the capability of compression seals and flashing; this is an even more severe problem with portable buildings erected on non-level ground.
2. The current sandwich construction approach of panels offers another entry point for water and dirt, contributing to their degradation.

There appears to be no single, simple concept in the solution to sealing problems. In fact, a system approach to optimize building designs around sealing would evolve as follows:

1. Use larger panels, to achieve fewer joints.
2. Use heavier, more accurately-leveled foundations, to contribute to structural integrity.
3. When absolutely forced to use a joint, caulk it with a hard, expandable substance.
4. Use peaked roofs with eaves, with shingle type construction if monolithic roofs cannot be used, to promote water runoff.
5. Use solid walls.

Following this approach, the designer might ultimately end up with a conventional non-portable building.

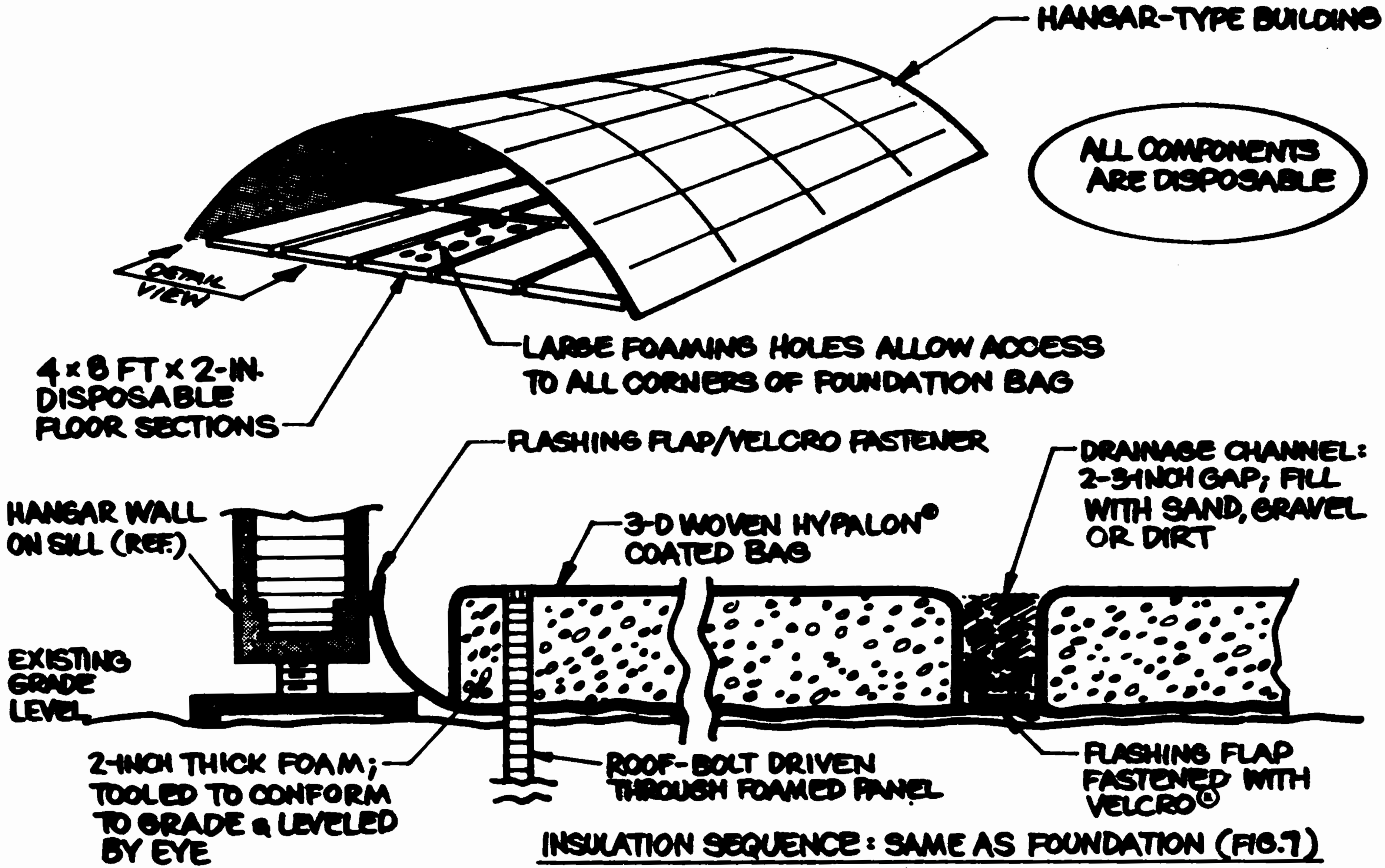


Figure 8. Floor Kit Concept

Nevertheless, new shelters should consider expanded uses of these approaches. Add-on climate kits could be used to alleviate the leakage problems that are expected to result from the use of large panels with integral sealing and flashing units. Figure 9 shows some recommended conceptual approaches to incorporating sealing into shelter elements. Some of these are, in fact, used in existing shelters. The ultimate result of using integral flashing, drain channels, closed sections, etc., is added fitting and joint complexity and weight. For this reason, the conceptual approaches appear attractive primarily when used in conjunction with molded panels and higher specific-stiffness materials. Additionally, weathering durability and damage resistance of currently used materials is a limit; the resulting indicated use of advanced, premium materials is discussed in subsequent subsections of this report.

The concept of add-on climate kits is to supplement the state-of-the-art integral sealing methods to be used with any advanced shelter. The requirement for the add-on kit is that it be a reusable, repairable, seamless, solid, impervious, flexible, lightweight building cover that is built up by coating a preferably nonwoven material with special function materials, such as reflective or absorptive materials. A shelter kit might be expected to have several covers included, because of the probable shorter in-service life of a fabric climate cover. The climate kit could provide the following functions on a "standard" shelter in a "severe" climate:

1. Solar heat load reflection or absorption
2. Insulation by means of dead-air space created
3. Blackout supplemental capability
4. Camouflage capability
5. Sound insulation capability
6. Flashing supplemental capability.

Figures 10 and 11 are schematic illustrations of the weather kit concept. Reference is made to Section V of this report for an evaluation of material candidates for such a kit. A typical cover would consist of a very thin Hypalon® membrane covering two woven Kevlar® fabric layers which are included to take tension loads used to tighten the cover over the shelter. Between the Kevlar layers would be an approximately one-fourth-inch layer of flexible foam such as polyurethane. Internal and external finish would be selected for solar control purposes, using the principle of selective α/ϵ ratios.

For example, a surface with the ratio $\alpha/\epsilon > 1$ will absorb radiant heat while the surface with the ratio < 1 will emit radiant heat. The result is a constant flow of heat if the two surfaces are connected such as in sandwich construction. This concept, when applied to shelters, allows the control of the flow of heat in a preferred direction. As an example, in the deployment of a shelter in the tropics, one would put the surface with the ratio $\alpha/\epsilon > 1$ on the exterior and the surface with the ratio $\epsilon/\alpha > 1$ on the interior. This configuration will aid the flow of heat from the shelter interior to the exterior where it will be emitted to the surrounding environment. For deployment in the Arctic the application would be the reverse; i.e., surface with the ratio $\alpha/\epsilon > 1$

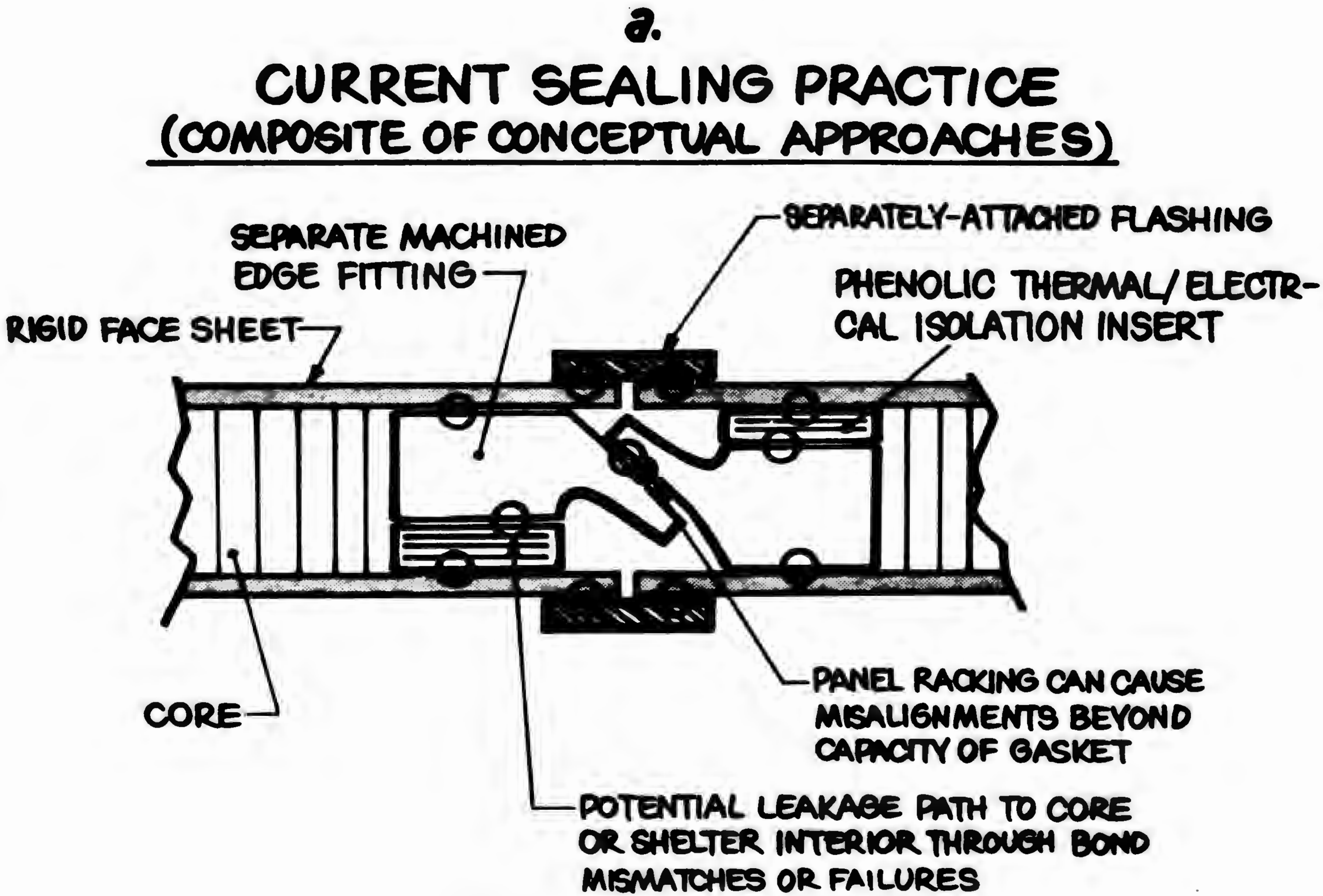


Figure 9. Integral Weather Seal Concepts

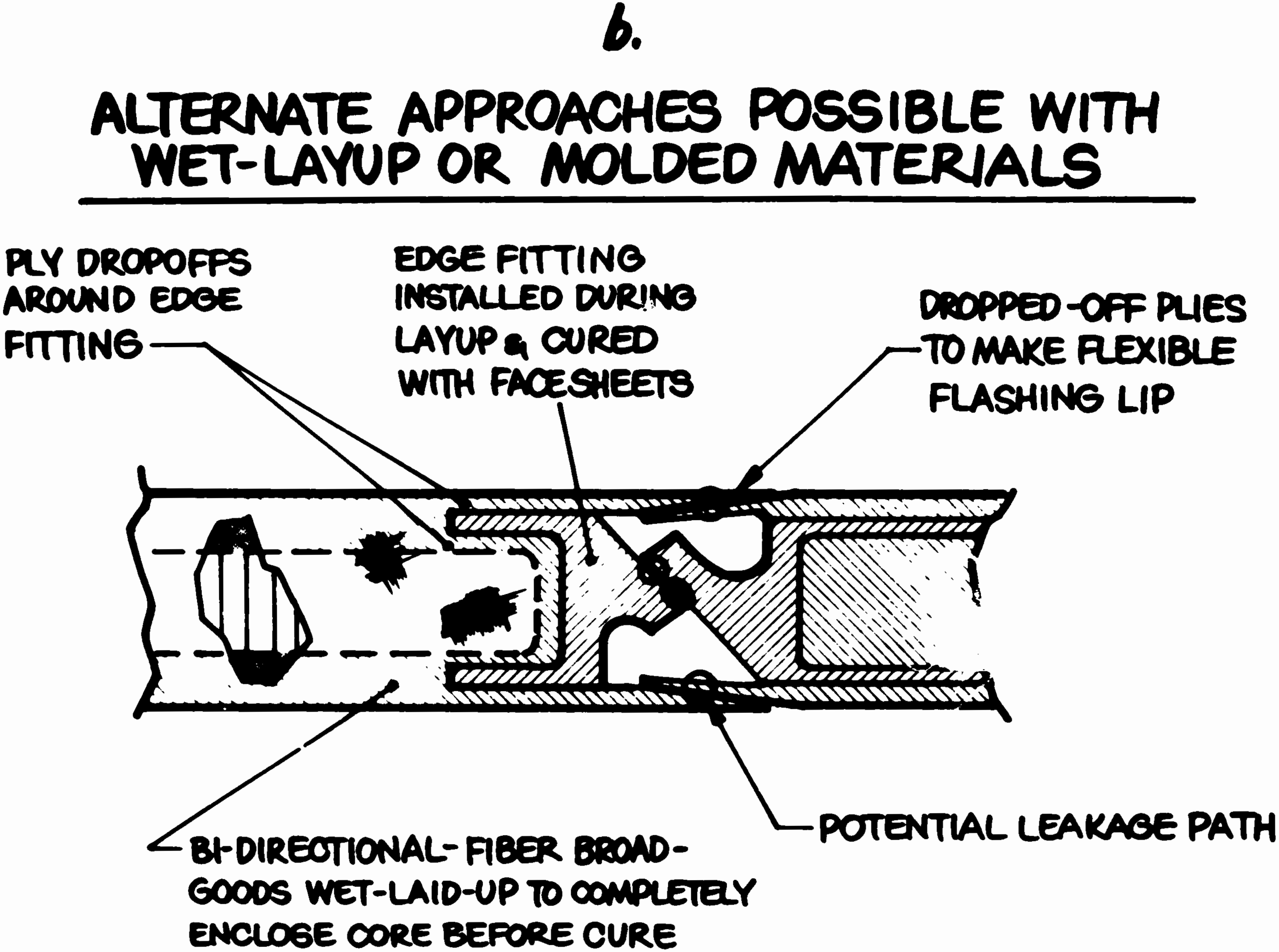


Figure 9. Integral Weather Seal Concepts (Concluded)

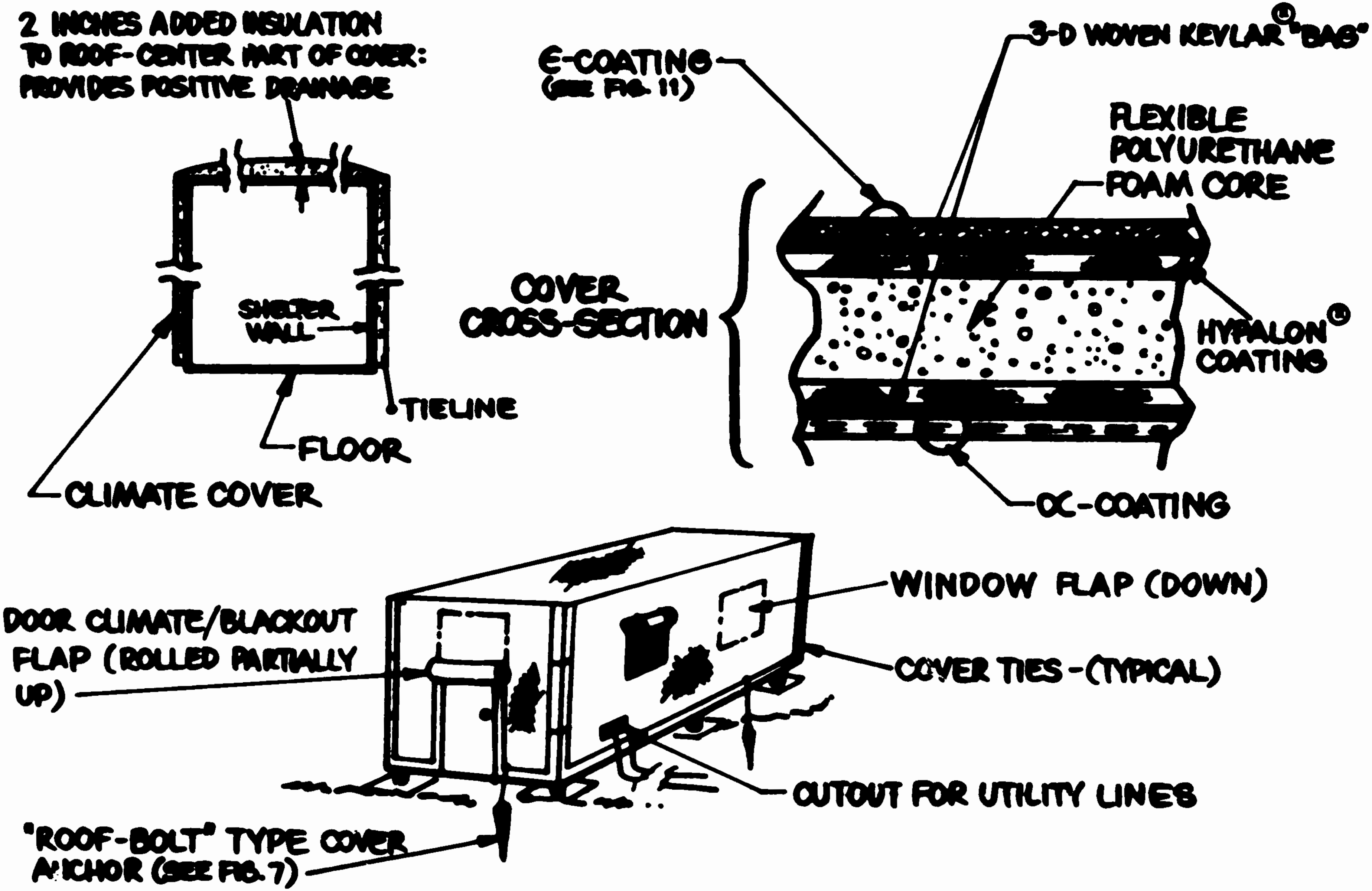


Figure 10. Climate Control Kit Concepts

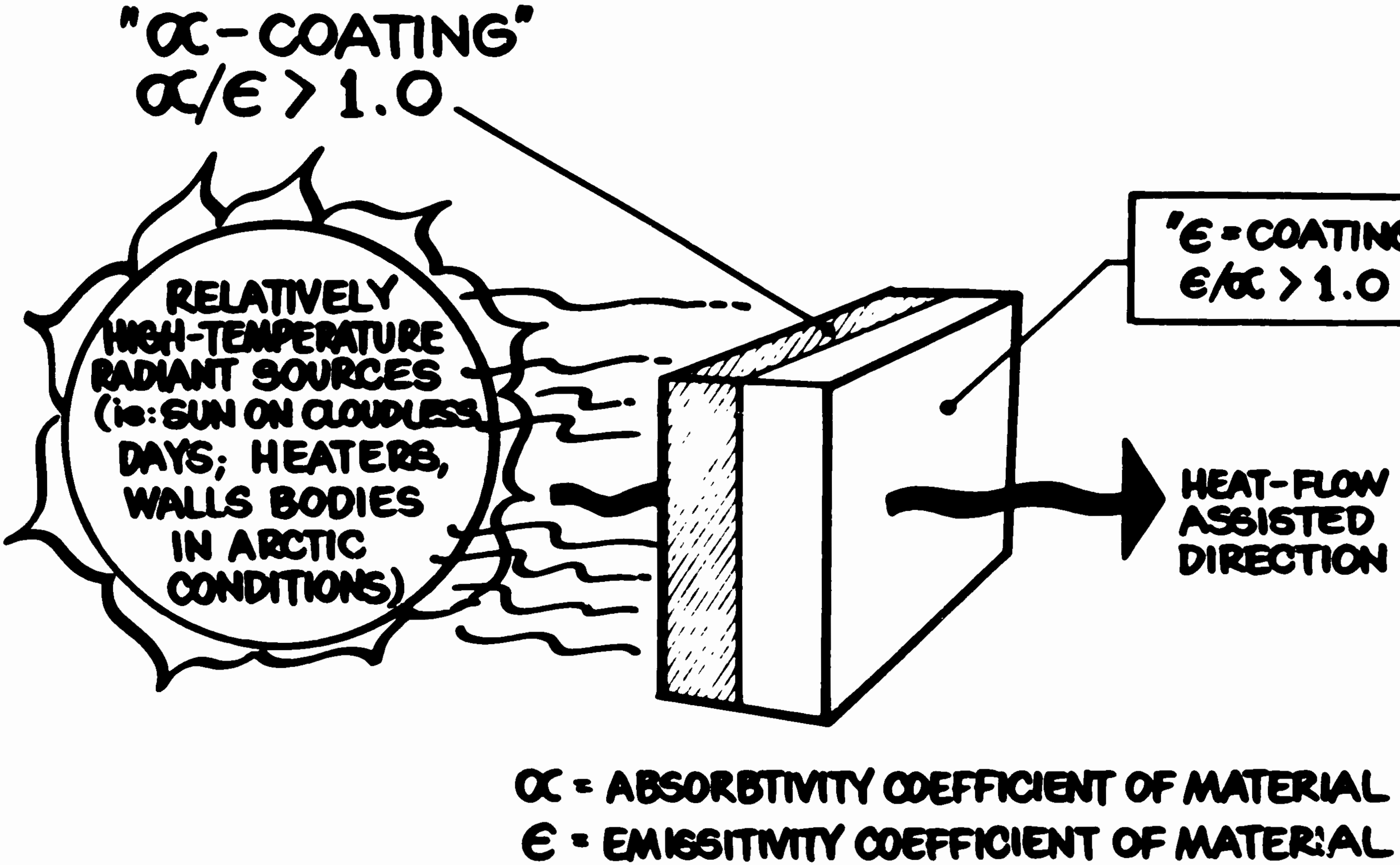


Figure 11. Climate Kit Concepts

on the exterior and the surface with the ratio $\epsilon/\alpha > 1$ on the interior to assure a flow of heat to the shelter interior.

Because material thermal radiation characteristics are dependent upon surface properties of color, finish and texture, it is possible to give a material the thermal radiation characteristics required for a given application. As an example, the covering material for a shelter, be it fabric, laminate or molded panel, can be finished on one surface to give a high α by dyeing or painting the surface dull black or gray. The resultant α will be 0.95 with an ϵ of 0.45. The other surface can be finished by dyeing or painting the surface a specular, glass white or light beige. The resultant ϵ will be on the order of 0.85 with an α of 0.45.

Another approach to climate kits would be to incorporate spray-on polyurethane foam kits with shelters. This concept is already well accepted in the commercial building field. The primary drawback when applied to mobile shelters is the permanency of application, which could be a hindrance to redeployment. Limited use for areas around joints is a compromise approach to use of this proven technology.

In general, the basis for forecasting the success of a builtup fabric cover weather kit is as follows:

1. The use of flysheets is well accepted in military shelters as a general approach (References 2 through 5).
2. Basic materials such as Hypalon®, and foam are already in general use in similar applications, such as pond liners and tents (Hypalon®) and insulation (foam); this provides the basic production base and development impetus for improving properties.
3. Kevlar® and comparable materials are already coming into wide use, which will tend to drive the price down to levels compatible with large scale use (References 42 and 43).

4.3.4 EMI Control Cover

A basic criteria in the Air Mobility Shelter Conceptual Study Statement of Work was the use of nonconductive materials. This approach provides some basic benefits relative to other requirements such as low thermal conductivity and corrosion resistance. However, the nonmetallic-material requirement thus imposed is basically incompatible with current methods of external-to-internal and internal-to-external EMI and RFI control. Therefore, it is suggested that:

1. Advanced family of air mobile shelters be designed to include no specific EMI and RFI control other than filters on electrical feed-throughs, which should be common on all shelters, whether or not a dedicated electronic-related use is intended for shelter.
2. EMI control via sizing of openings such as windows and other gaps in the structure should not be a design goal of the shelter.
3. EMI control should be provided by a strap-on flexible cover that has openings, if any, sized for particular bands of wavelengths, and which surround the building, including the floor.

4. The material used for the cover should be flexible and provide the same general installation provisions as noted previously for the climate control kit.
5. The EMI cover should be constructed in the same manner as the climate cover, but with the addition on the shelter-side of the cover of the EMI control material.

Reference 27 contains an excellent discussion of the material thickness requirements for EMI attenuation. The material problem posed for an EMI cover concept is to provide this attenuation capability with a flexible material. Reference 44 discusses a successful experimental use of a nickle-whisker filled elastomer being used to "pot" electronic components by compressing the filled elastomer.

This approach could be used in a flexible EMI control cover. The elastomer filler, uncompressed, could be limited to a fiber-matrix volume ratio that is amenable to spraying on as a coating. The process of tensioning the coated cover would provide the additional elastomer/filler material to provide the necessary EMI attenuation.

Figure 12 is a schematic illustration of an EMI control cover concept. Note that the cover can contain reduced-size window openings, including gold-filled flexible plexiglass panes, for increased EMI control.

4.3.5 Universal Container/Pallet Kit

The basic approach recommended for an advanced-concept shelter family is to separate to a larger degree than is currently done in the Bare Base shelter system the function of shelter and mission-equipment container. In a general sense, the Bare Base approach has resulted in shelter/containers non-optimized for either use. Similarly, the Seabee Quick Camp containers demonstrated this same shortcoming when modified to create portable shelters. At the same time, however, cognizance is given to the original intent of the entire 437A System to integrate the functions. Reference 3 also cites field data to the effect that noncontainerized mission equipment typically suffers a 20-percent pilferage and loss rate during an overseas deployment.

Therefore, an additional concept for inclusion in a future shelter is a universal container/pallet kit. The kit would perform the following functions:

1. The base unit would have provisions for, or capability for, being skidded; rolling on 463L roller conveyors; stacking on ISO containers; and would have a shock-suspension floor and flush integral hooks for cargo tie down.
2. The framework would be foldable into the base unit so that base units could be stacked.
3. The framework/base combination carries the shipping/handling loads.
4. Snap-in rigid sides provide cargo protection from penetration and pilferage, but are not required to sustain stacking, racking or lifting loads.

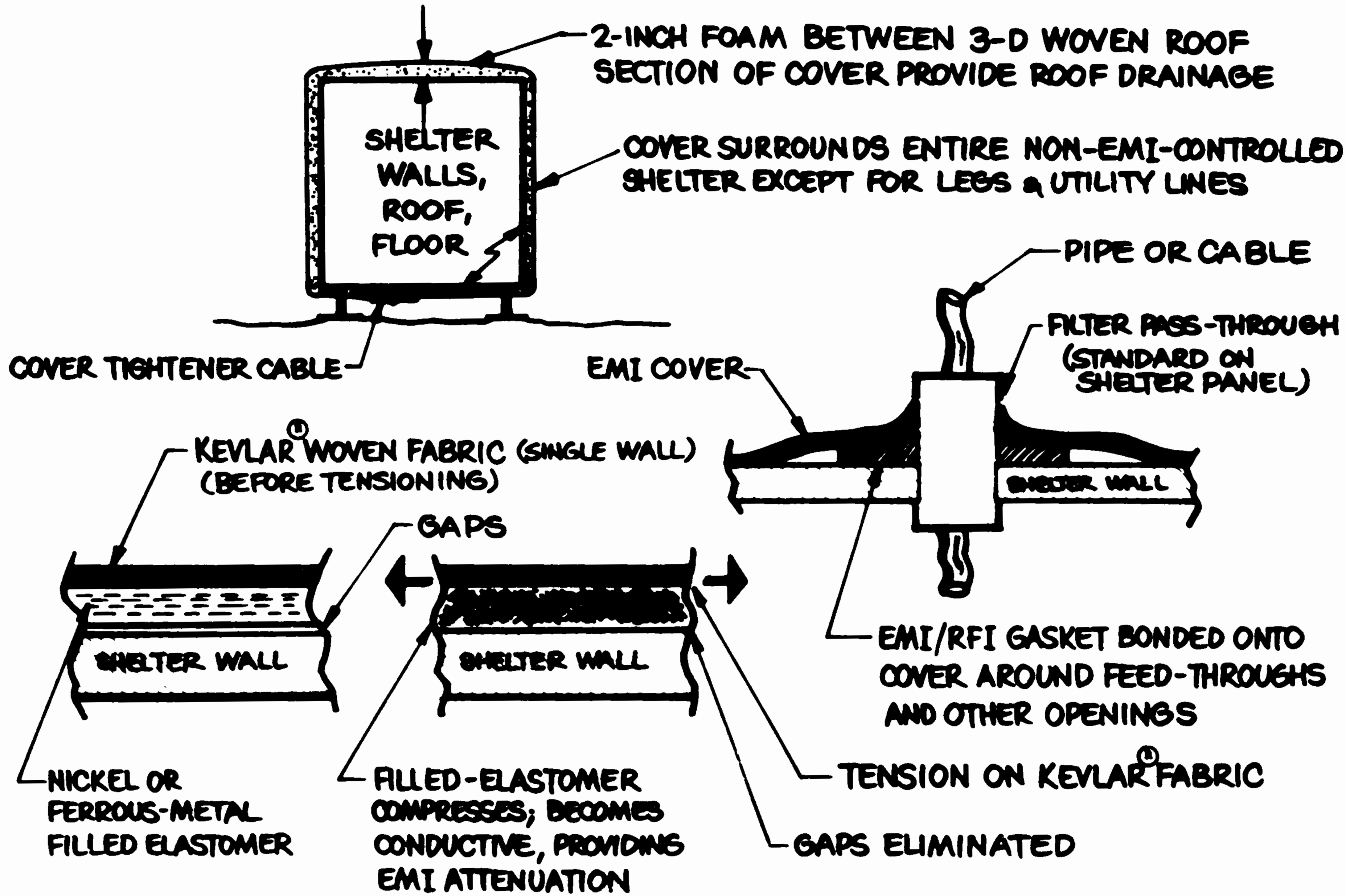


Figure 12. EMI Control Cover Concept

5. An internal tie down cover would be provided for cargo weather protection.

The container/pallet kit could be used to carry other shelter kits; spare shelter panels; and mission equipment. The base unit could also be designed to function as a basic shelter floor. Figure 13 is a schematic illustration of the universal container/pallet kit concept. The design goal is to provide a container with the strength and rigidity of current ISO containers, with a 50-percent weight reduction, by sacrificing basic weather tightness and wall stiffness.

Materials used could be as follows:

1. Pultruded epoxy/aramid-fiber, closed-section framework beams, with integral fittings.
2. Base unit panels and snap-in side walls would be made of chipped-fiber-epoxy moldings with integral stiffening ribs; unidirectional fiber/epoxy tapes would be bonded on to provide necessary stiffness in the area of load-introduction points, which would be molded from ultra-high-molecular weight polyethylene.
3. The fabric covers would be Hypalon® coated woven Kevlar® to provide an impermeable, penetration resistant envelope over mission equipment.

4.4 ONE-PIECE STRUCTURAL SECTIONS

In order to minimize the recurring labor cost in shelter fabrication, such as is commonly involved in hand-assembly of sandwich panels, advanced materials can be used in conjunction with automated manufacturing methods to produce panels, beams, and covers with integral stiffeners; integral close-outs and joints; integral hinges, and formed-in window, door, and vent openings.

There are several additional benefits from this approach, such as:

1. Minimization of load paths that are discontinuous at fastened joints.
2. Avoidance of dependence on complex bonded joints.
3. Eliminating costly secondary operations involved in removing material from standard sections solely for weight reduction.
4. Limiting the use of closed sections such as sandwich structures with honeycomb or foam core that can collect and hold moisture.

Figure 14 schematically illustrates the conceptual approach to one-piece structural sections by comparing the sections to the current practice in shelters.

The manufacturing processes for these concepts are discussed in Section V of this report.

4.5 USE OF PREMIUM MATERIALS

An alternate approach to advanced air mobile shelters would be a direct materials substitution redesign program for current air mobile shelter designs, retaining all external dimensions, operating geometries, and "moldline"

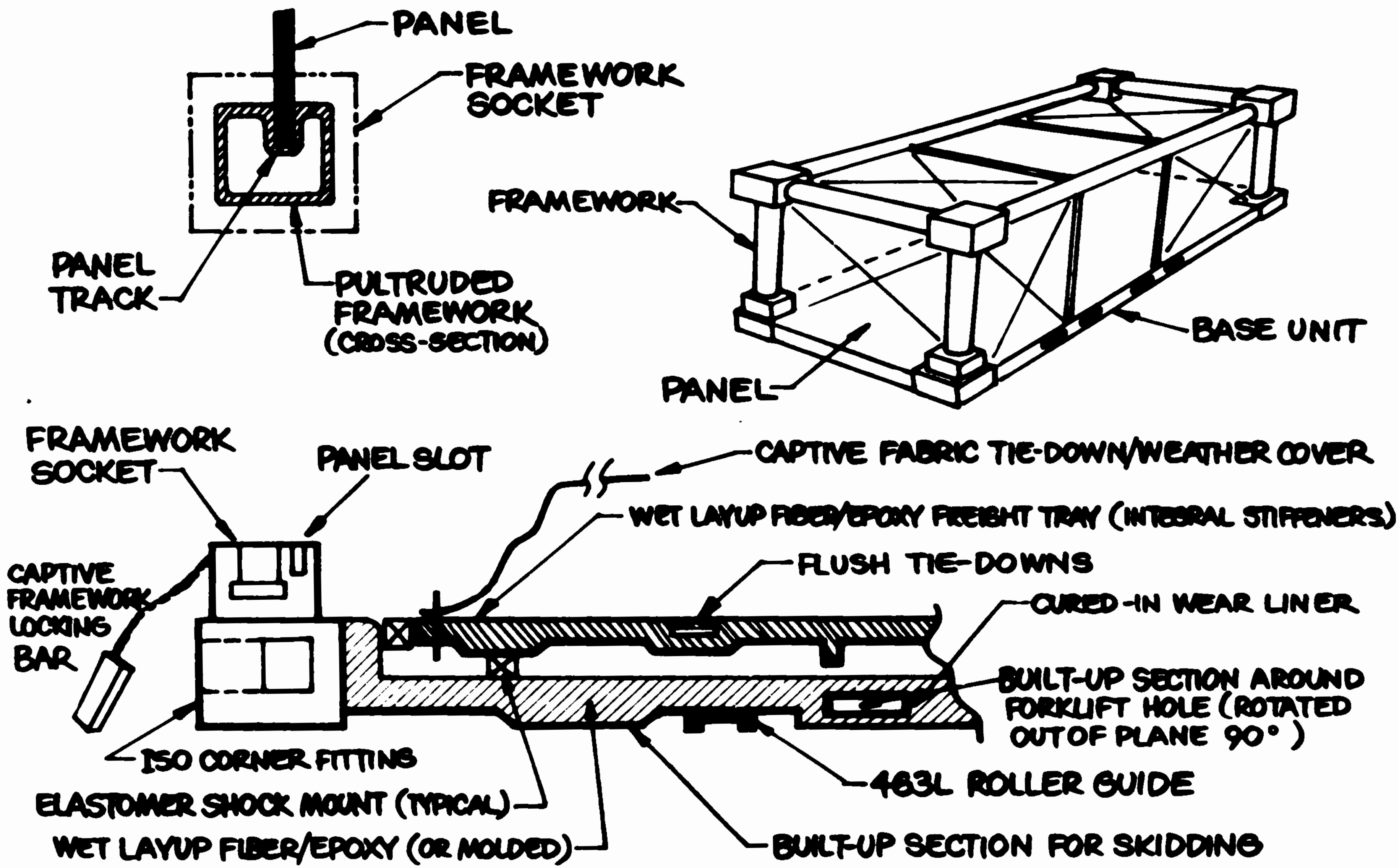


Figure 13. Universal Container/Pallet Kit Concept

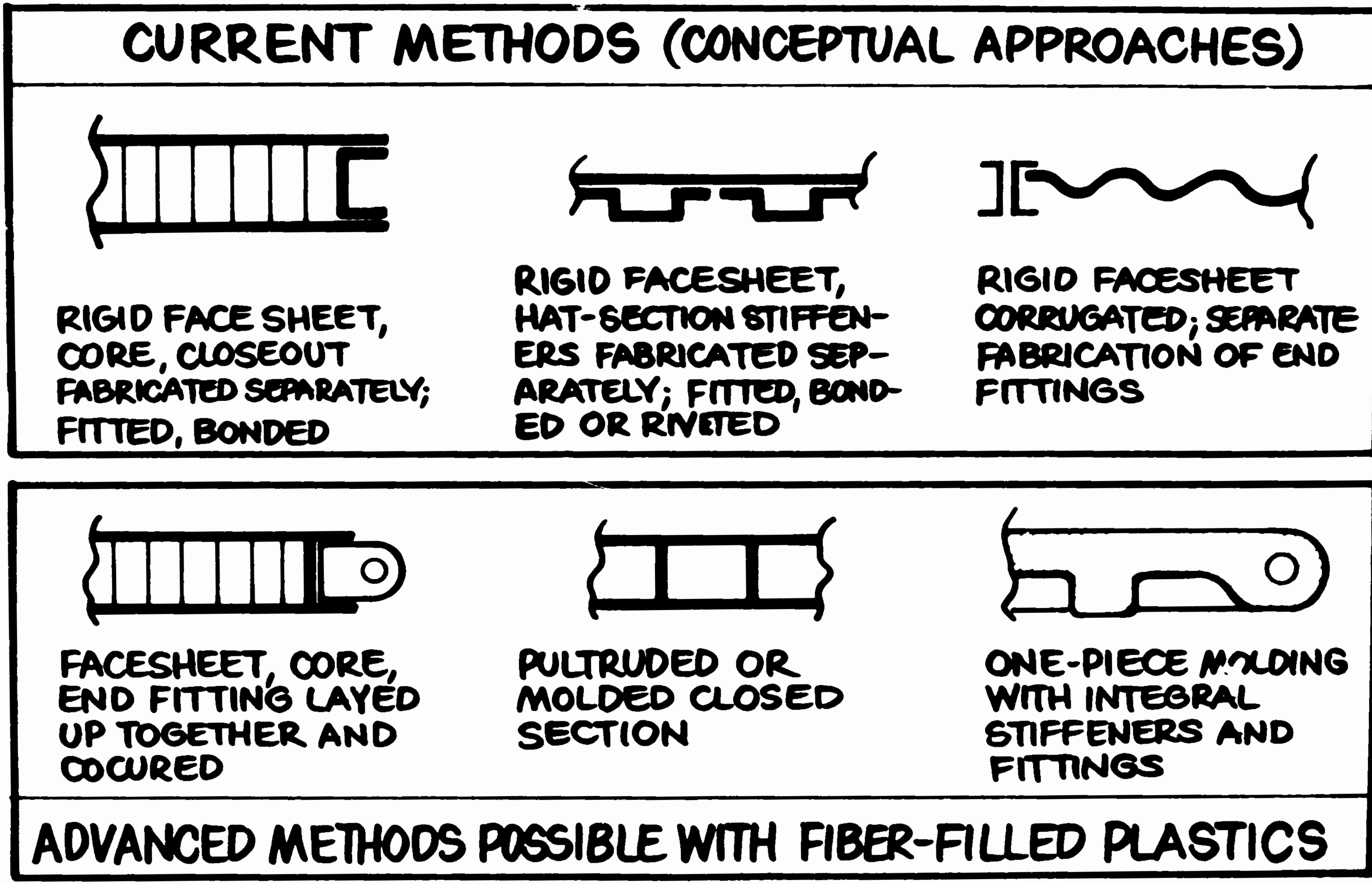


Figure 14. One-Piece Structural Section Concepts

dimensions unless specifically required to be changed by the use of the substituted material. An example of this approach is the planned trial of polycarbonate molded panels in the LocArch shelter.

Table 8 is a representative selection of material substitutions, using premium materials currently available. The literature reviewed frequently mentions use of these materials as "considered but rejected because of high first cost."

4.6 NEW SHELTER FAMILY

Existing single-shelter concepts and shelter-family concepts could be upgraded by material substitution in individual elements, using any or all of the subelement concepts discussed previously in this section. However, if square-footage/mission/deployment scenarios for the 1980's were established, it might be economic to procure an all new shelter family for bare-base type operations, with initial operational capability targeted for early in that time frame.

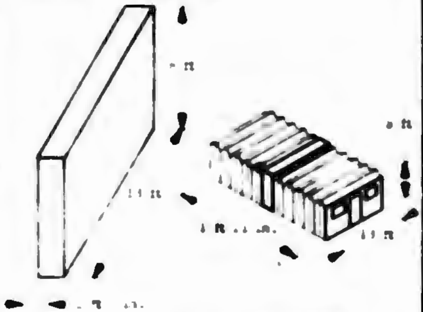
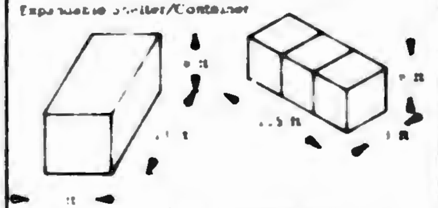
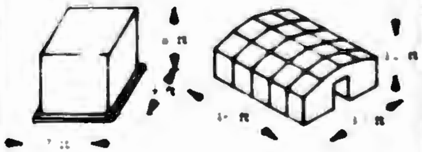
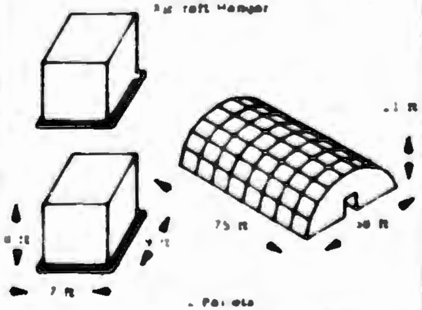
4.6.1 General Description

The shelter concept evaluation in Sections II and III generally indicated the acceptable-to-superior range for rigid-wall expandable shelters. In addition, the advanced materials forecast for economical availability in the 1980's is largely usable in rigid wall concepts. Therefore, a suggested approach to an all-new shelter family that (1) retains good features of the basic concept, (2) achieves durability by use of premium materials, and (3) makes maximum use of high specific strength and stiffness materials is generally configured as shown in Figures 15, 16, 17, and 18.

The "family" shown is somewhat similar to the "large/small family" presented in Reference 27. There is also a family resemblance to the Goodyear Hardwall Expandable shelter concept. Joints are based on the Brunswick concept of Reference 32. The extension in technology from these concepts is primarily as follows:

1. The hangar can be constructed without rafters, using only adapter/purlins (Figures 15 and 18) because the panels are forecast to be about 30 percent stiffer and 30 percent lighter than Bare Base panels, with equivalent wind and snow-load capabilities, by use of pultruded or compression-molded, aramid/epoxy composites.
2. The joint concept of Figure 9 is an improvement in both sealing and eccentric load capability because of the use of integral panel-closeout construction, using metal-oxide/epoxy materials.
3. The tendency toward high cost of a multiple-use floor/roof panel, with many attachment provisions, is counteracted by using one-piece construction, possibly with compression-molded chopped-fiber-reinforced/epoxy core covered with selective reinforcement of oriented continuous-fiber/epoxy tape.

TABLE 8. PREMIUM MATERIALS SUBSTITUTION

SHELTER PICTURE (SHIPPING / EXPANDED)	MATERIALS OF CONSTRUCTION	PROPOSED MATERIALS OF CONSTRUCTION	ADVANTAGES
Expandable Airborne Shelter  11 to 1 Expansion Ratio	**Expandable Wall:** Polyvinyl Chloride Coated Kraft Paper ... Sandwich with a Urethane Foam Core **End Walls:** Fiberglass Skins with Impregnated Balsa Core **Center Section & Floor:** ... Aluminum Skins/Paper Honeycomb or Foam Core Sandwich	**Expandable Wall:** (1) Polyvinyl Chloride ... Skin, Foam Extrusion (3 lb/cu ft) Panels. (2) Polyurethane Coated, Kevlar Fiber Laminate Skin with Rigid Urethane Foam Core. **End Walls, Center Section and Floor:** Kevlar Epoxy ... Skins with Kevlar Honeycomb Core or Nomex Core	(1) [illegible] (2) [illegible] for Exclusion of Moisture [illegible] Very [illegible] Moisture Resistant [illegible] Light Weight [illegible] Structure [illegible]
Expandable Shelter/Container  3 to 1 Expansion Ratio	**Walls, Ceilings, and Floors:** ... Aluminum Skins Paper Honeycomb or Foam Core Sandwich	**Walls, Ceilings and Floor:** (1) Integrally ... Polycarbonate Panels (2) [illegible] (3) Kevlar Epoxy ... sheets, Nomex Core	(1) [illegible] (2) [illegible] (3) [illegible]
General Purpose Shelter 	Modular Design, Double Hinged Aluminum Beams, Panels ... Aluminum Skin with ... Honeycomb Core Sandwich	**Beams:** Fiberglass Epoxy ... Molded Laminate ... or Kevlar ... Epoxy ... Extrusion ... Shape (pultrusion)	[illegible]
Aircraft Hangar 	Same as General Purpose Shelter with Interchangeable Parts	**Panels:** One Piece Injection Molded Kevlar or Fiberglass ... Polycarbonate Panel ... Molded ... Same Material with ... Core	[illegible] Resistant

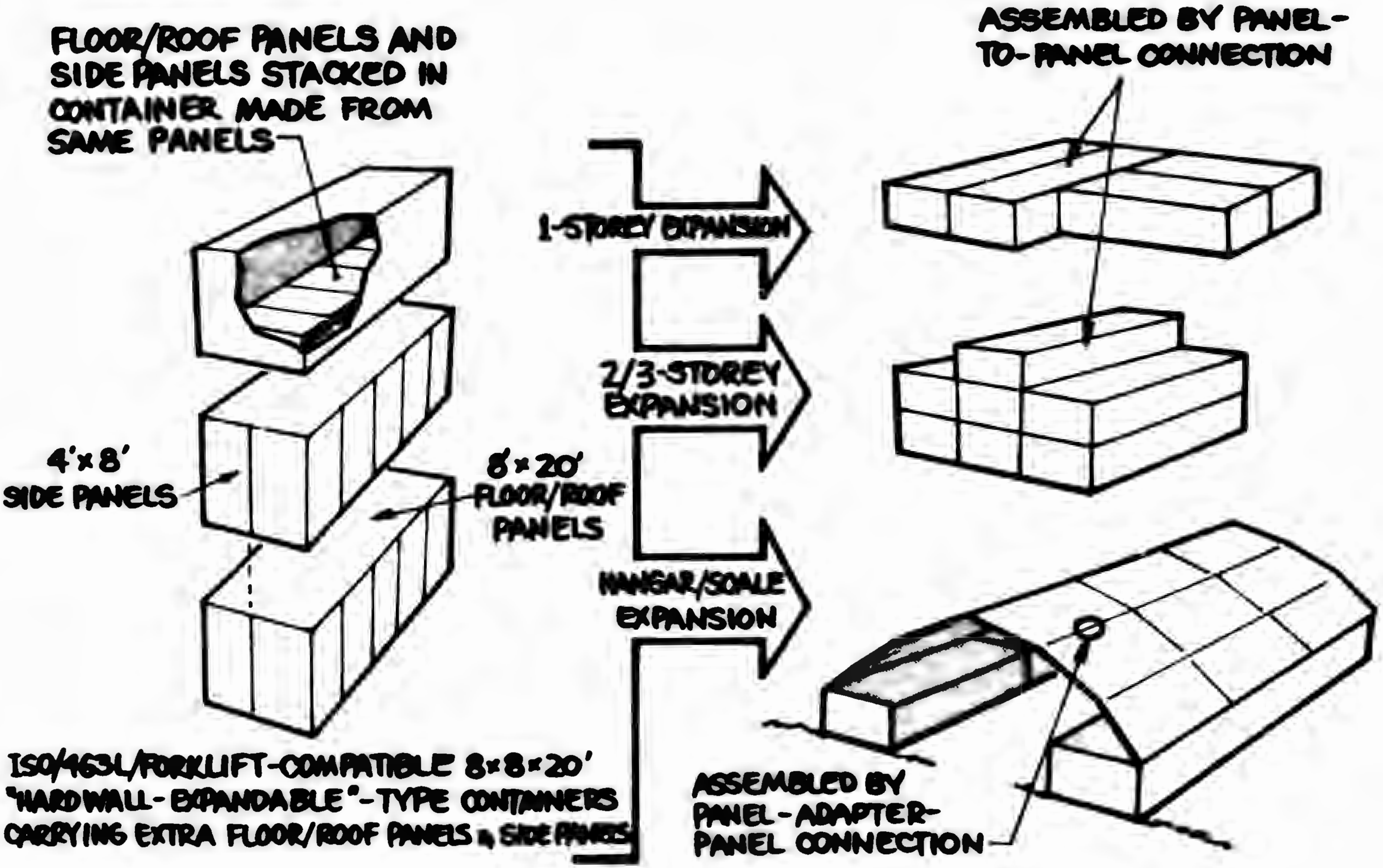


Figure 15. Shelter Family-Basic Concept

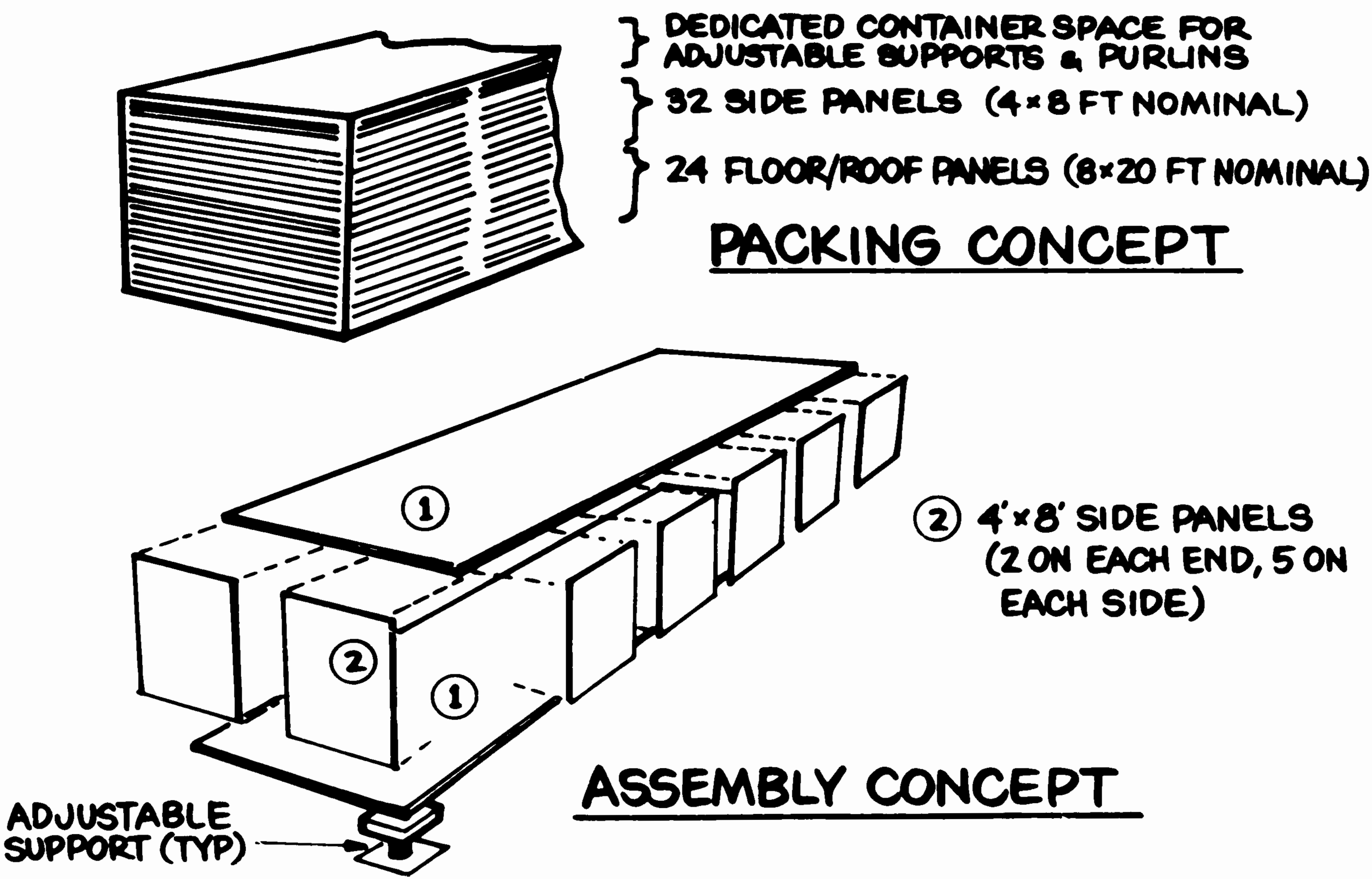


Figure 16. Shelter Family-Packing Container Concept

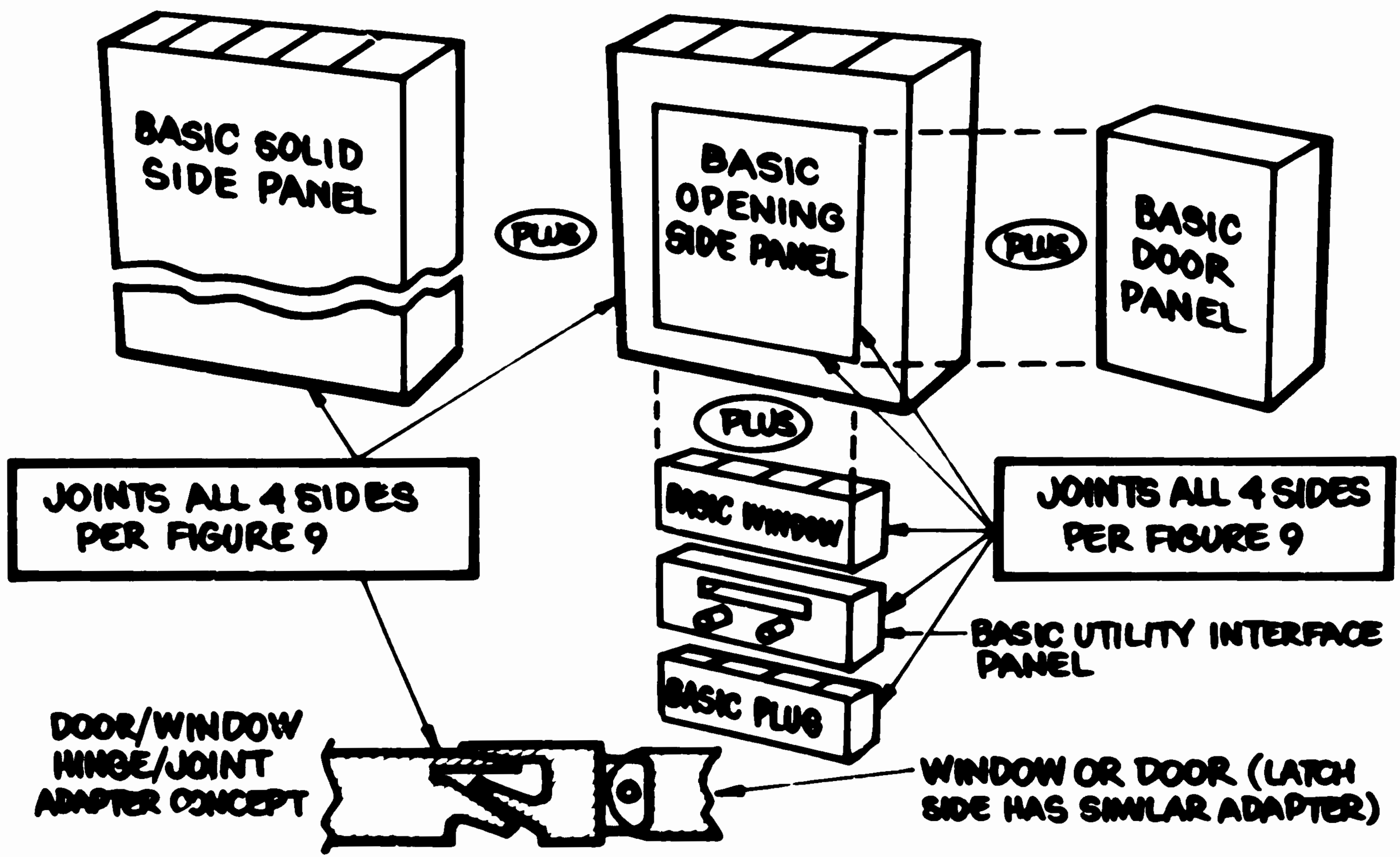


Figure 17. Shelter Family-Side Panel Concepts

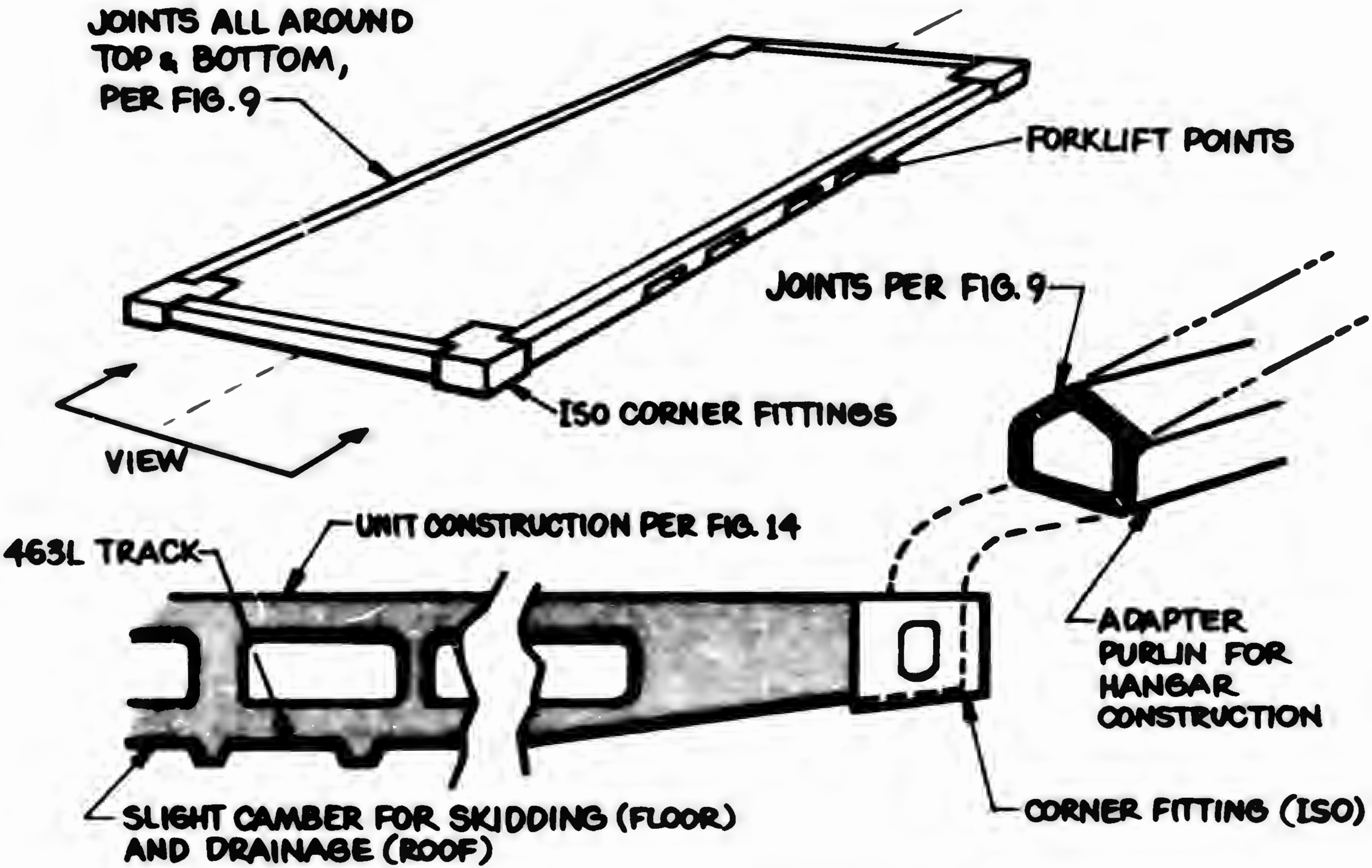


Figure 18. Shelter Family-Floor/Roof Panel Concepts

A basic philosophy with the shelter family concept shown is the maximum use of common, standard panels. The panels in a set are:

1. A 4 by 8-foot side panel with no openings.
2. A 4 by 8-foot side panel with a door size opening.
3. "Plugs" for the side panel with the opening:
   a. A solid half height plug
   b. A half height window
   c. A door
   d. A half height utility feed-through panel
4. An 8 by 20-foot floor/roof unit that contains all provisions for transport compatibility.
5. A "purlin" that allows a non-orthogonal installation of a mating side panel or floor/roof panel.

The system specification would require that the utility system and/or the mating mission equipment installed in the shelter include the necessary adapters to interconnect with the utility panel, rather than provide for mission-specific utility panels.

The roof panels would have molded-in recesses for wire duct runs and molded-in hangers that could be used for suspended air ducts, curtainrods, lights, etc.

When the shelter is expanded, side panels, with or without doors or windows, can be left installed to provide interior partitions, or interior load-bearing walls, as required. This feature allows stacking of modules to create two-story buildings or high-bay buildings.

Compared to foldout-type concepts, the joint concept used requires a relatively large amount of assembly time, even with the use of 1/4 turn captive fasteners. In addition, the manipulation of the floor/roof panels would require supplementary bracing (and hoisting equipment, in the case of the hangar-scale buildings). There is probably some good temporary arrangement of the side panels that might be devised for use as an erection aid, however.

The shortcomings noted in the previous paragraph can be overcome by the "permanent-quality" features of the building.

Wherever basic-module shelter units abut each other, supplementary flashing is required. This is one reason that the large floor/roof panel size was selected: to minimize the number of joints. Snap-in hard vinyl flashing is the preferred approach for this application. Semi-permanent flashing installation could be made by use of a solvent-softenable adhesive to bond on the flashing.

All of the "supplementary kits" are described elsewhere in this shelter family concept.

In summary, the shelter family concept presented is capable of meeting all of the specific requirements of Table 7, and score very highly in a rating where there is a range of requirements stated.

4.6.2 Load Analysis

The basic concept of a common side panel results in a panel that is overdesigned for some applications, such as interior walls and some sidewalls. The actual panel design should be the result of a selection of the actual building sizes to be provided. To examine the effect of design-requirement loads on a range of building sizes, parametric analysis of span/load/moment was done on a unit-load basis; this illustrated the relatively small sensitivity of design moments and material usage to building shape, over the range of building sizes most likely to be required. It was for this reason that simple flat-panel, box-like structural approaches were used.

Three basic configurations which were representative, relative to the application of advanced materials, of all future shelters envisioned were considered. These configurations, shown on Figure 19, are: (1) a flat roof frame, (2) a ridge roof rigid frame, and (3) a two-hinged circular arch with the spring line on the chord.

Shelters of these basic configurations ranging from a minimum 8-foot headroom to 28-foot headroom and of any length desired were analyzed to determine both material strength and thermal requirements.

Figure 20 is a flow diagram for the evaluation of shelter efficiency relative to selected configurations.

The mechanical and thermal properties required in advanced materials can be determined by finding the strengths and thicknesses required to meet the environmental loads imposed on a full range of shelter configurations by the shelter system requirements.

Each configuration is also evaluated for efficiency in performing three major shelter functions:

1. Provide a weather shield
2. Provide a thermal barrier
3. Act as a load transfer mechanism.

4.6.2.1 Weather Shield Efficiency.

One method for measuring efficiency of shelters is to consider the cost of covering a given amount of usable floor area. Two types of costs are involved. The cost of materials and fabrication, and the life cycle cost.

The initial costs and the costs associated with heating and cooling are a function of the surface area of the shelter. The surface area of covering required per square foot of usable floor area has been determined and is shown in Figure 21 for the representative configurations. The flat roofed configuration will require the least amount of covering per usable floor area and is used as a baseline for the evaluation of the other configurations. The ratio of covering area as a function of span length and configuration is shown in Table 9. These figures and tables permit evaluation of the initial costs of materials required as well as the heating and cooling costs associated with deployments in various locations. For example, in all cases the circular arch configuration

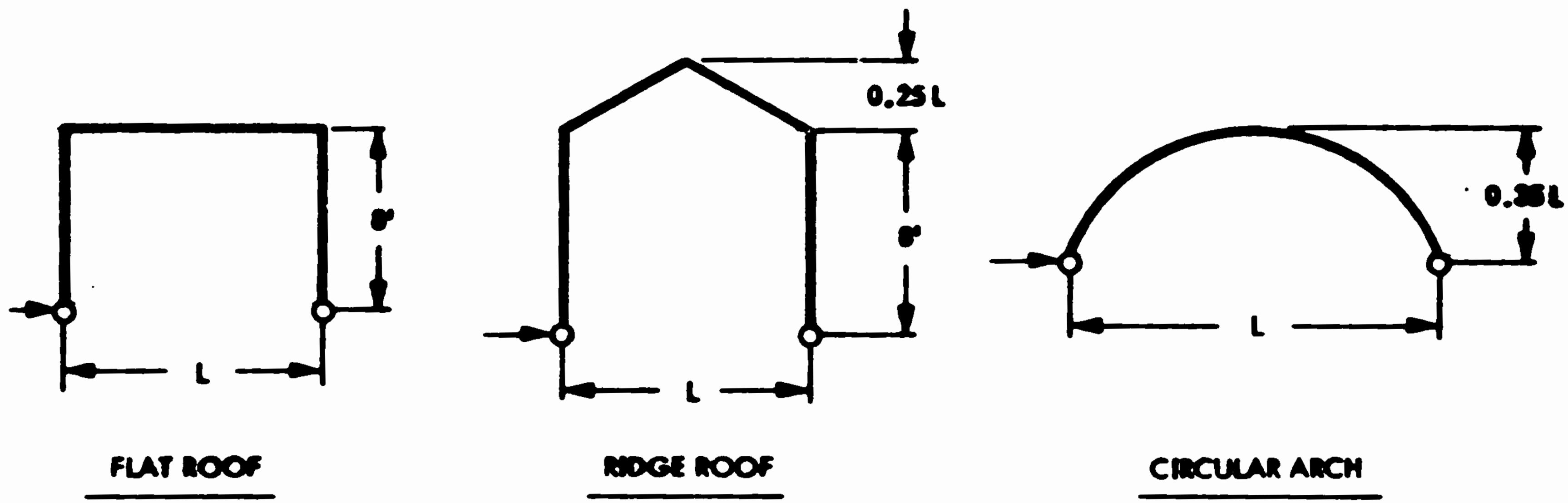


Figure 19. Basic Rigid Frame Shelter Configurations

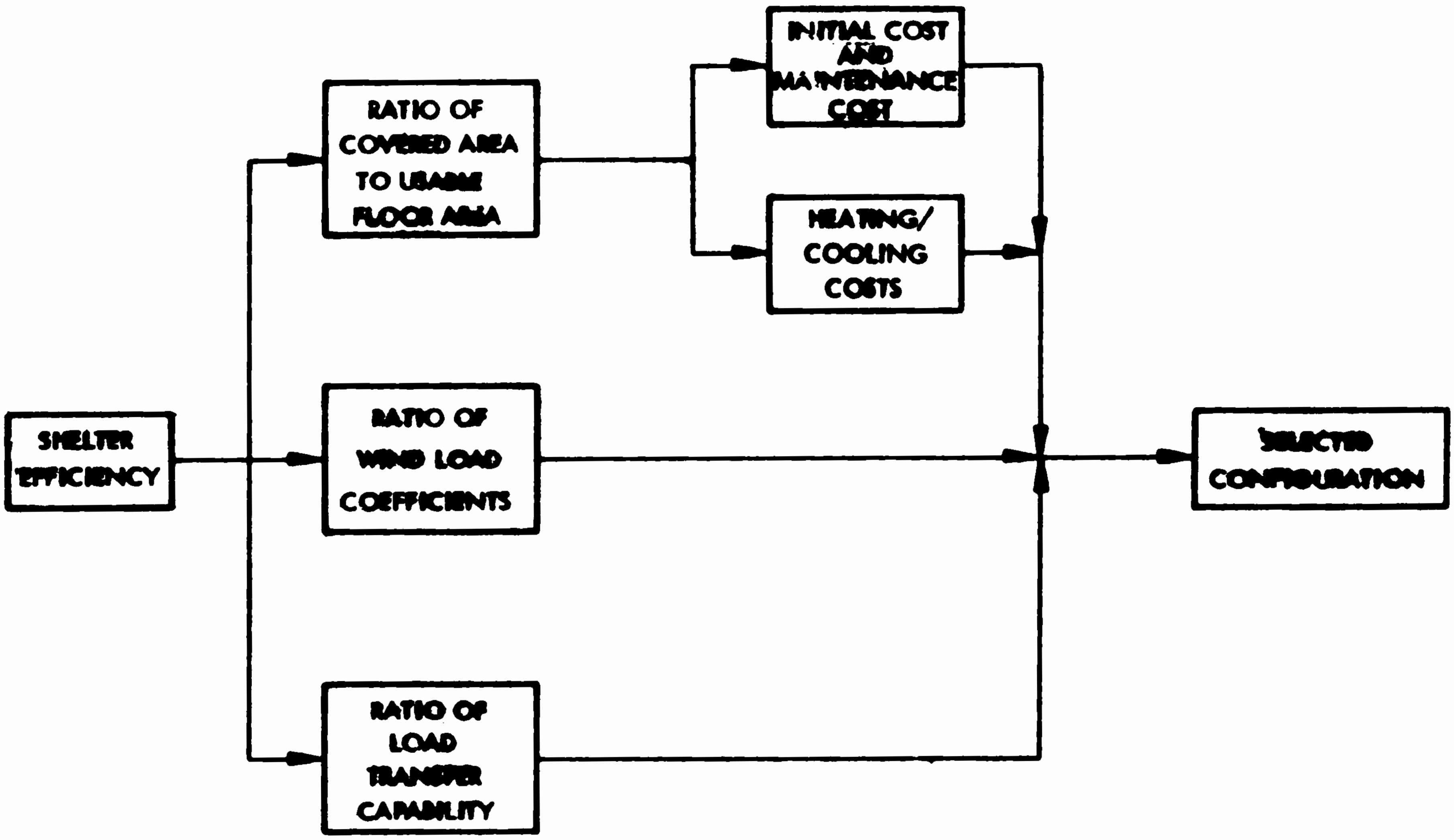


Figure 20. Flow Diagram - Evaluation of Configuration Efficiency

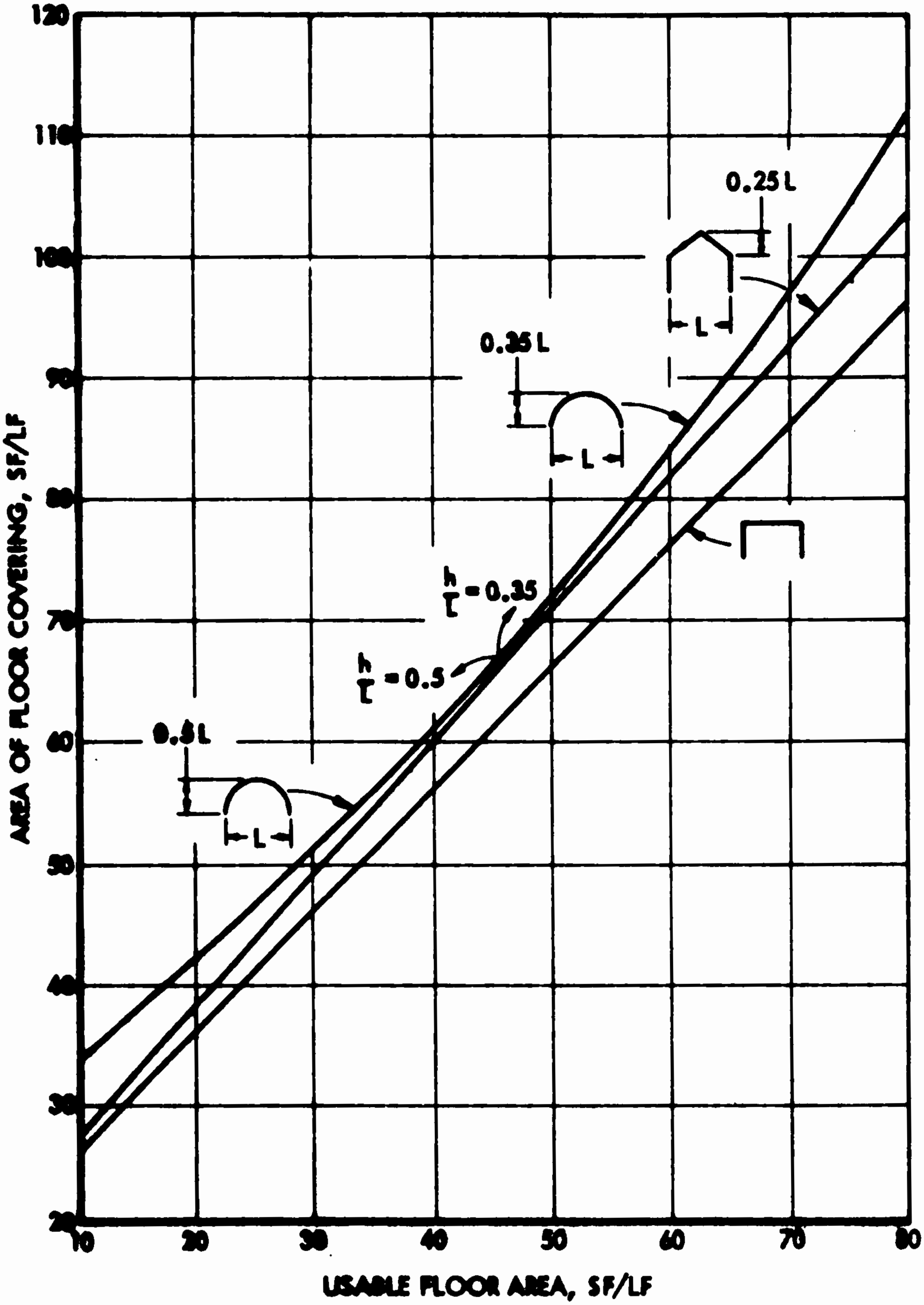


Figure 21. Area of Structural Covering Per Usable Floor Area

TABLE 9. RATIO OF INITIAL COVERING COST AND HEATING/COOLING LOADS AS A FUNCTION OF CONFIGURATION

CONFIGURATION (8' HEADROOM)	SPAN, FEET							
	10	20	30	40	50	60	70	80
FLAT ROOF	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RIDGE ROOF	1.05	1.07	1.08	1.08	1.08	1.08	1.08	1.08
CIRCULAR ARCH	1.31	1.17	1.11	1.09	1.09	1.11	1.13	1.17

requires from 9 to 31 percent more surface covering material than the flat roof and from 1 to 26 percent more material than the ridge roof configuration.

4.6.2.2 Thermal Barrier Efficiency.

The shelter covering, in addition to being a weather shield, performs as a thermal barrier. The ratio of heating or cooling loads as a function of configuration can be determined from Table 9.

4.6.2.3 Load Transfer Mechanism Efficiency.

The relative efficiencies of the three configurations as structural load transfer mechanisms have been determined for various loads imposed on the structure. These loads shall consist of a uniform unit vertical downward load, the appropriate wind load coefficients resulting from a unit horizontal wind load, and unit point loads at any point on the structure. Design bending moments shall be determined and the relative design bending moments compared. The design bending moment is used on the basis that the material is homogenous and elastic so that sectional properties are determined by the maximum bending moment regardless of sign.

The design bending moments have been calculated for a uniform vertical unit load for a flat roof configuration not fixed at the wall junction, for a ridge roof not fixed at the wall junction and for a circular arch. The results are shown in Figure 22. The ridge roof configuration,due to the pitch, has a horizontal component at the roof-wall interface which induces a bending moment in the wall section at the footing level. This bending moment is also shown in Figure 22 and assumes fixity at the foundation level.

The data of Figure 22 indicates that the arch is approximately 12 times more efficient (requires less material) than the flat roof and 6 times more efficient than the ridge roof. However, this data is misleading for the configurations in Figure 22 are not compared on an equal basis. Of the three basic configurations, only the two-hinged arch (a rigid frame) is fundamentally stable and inherently distributes moments throughout the frame. The other two configurations, the flat roof and the ridge roof, have to be made stable by fixing the connection at either the roof-wall junction or the foundation. For this study both the flat roof and the ridge roof will be considered fixed at the roof-wall junction and pinned at the foundation level. This assumption is more realistic than designing for no rotation (fixity) at the foundations. The three configurations will be considered to be rigid frames for all future calculations and comparisons. In addition, all frames are considered to have members of equal and constant cross-section and that they are not tied together at the ground line; i.e., no load transfer between the wall and the floor member.

In rigid frames, particularly of large spans, it is common practice to use tapered members and to add additional material at the haunches. To determine the effect of the assumption of constant section for all frame members, the data of Table 10 is presented which covers a wide range of height-to-span

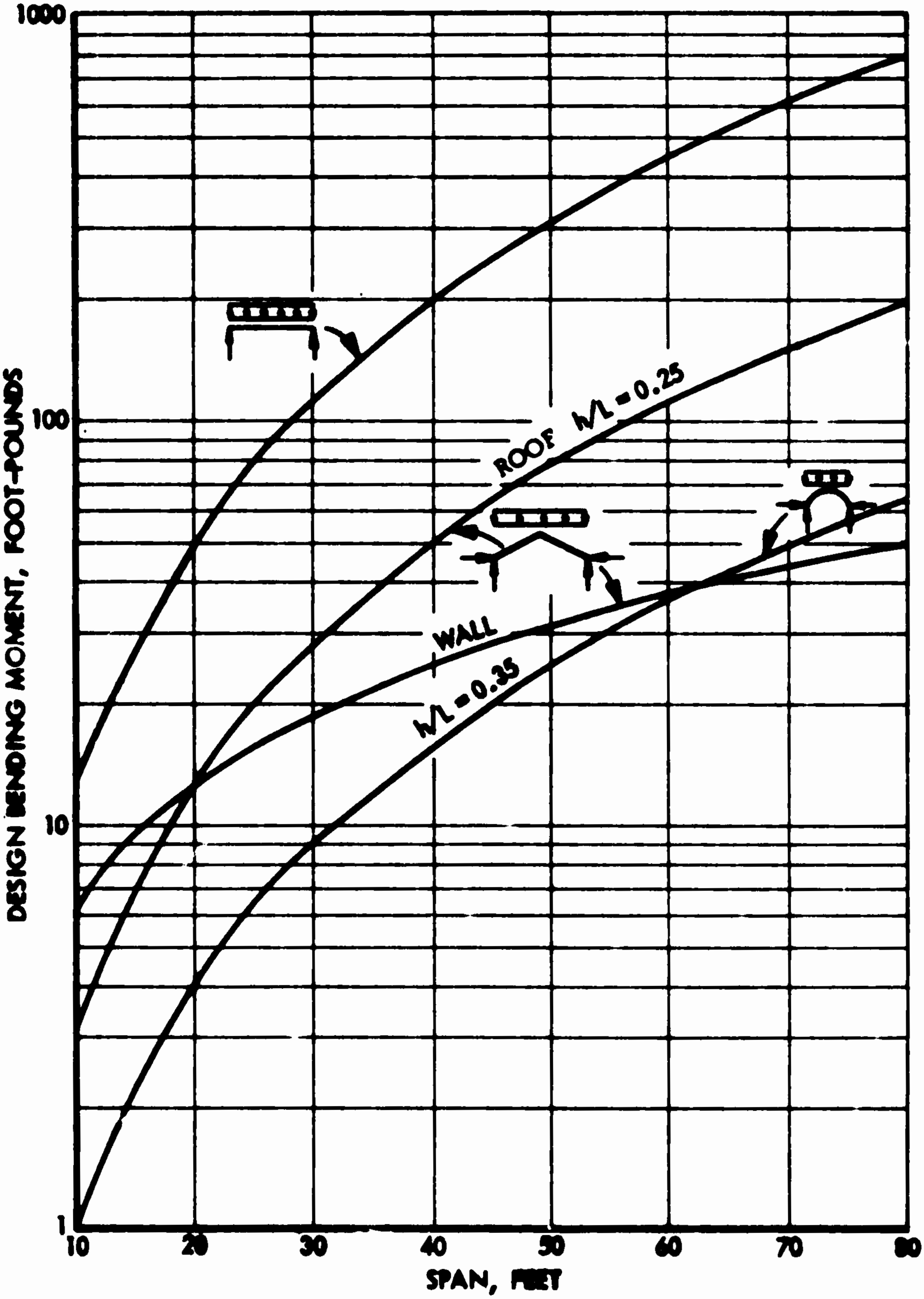
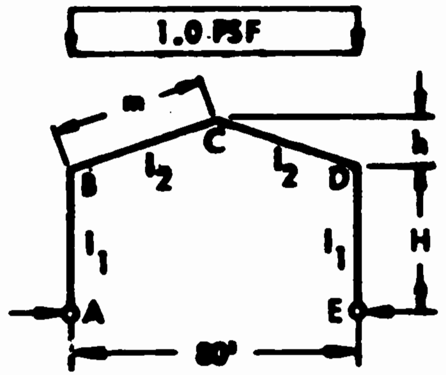
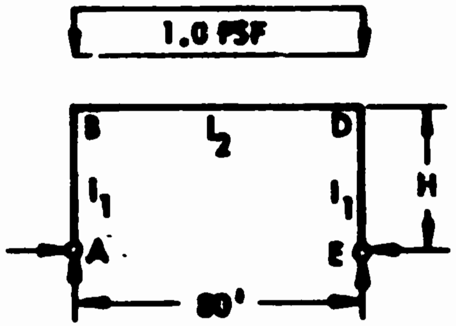


Figure 22. Design Bending Moment for Uniform Unit Vertical Load as Function of Structural Configuration

TABLE 10. EFFECT OF RELATIVE MOMENT OF INERTIA OF FRAME MEMBERS ON MOMENT DISTRIBUTION

CONFIGURATION	H/L	h/L	$h I_2 / m I_1$	Moment (ft-lb)		Moment (ft-lb)		Ratio
				M_D	Var. Percent	M_C	Var. Percent	M_C/M_D
	0.125	0.25	0.5	274.56	+0.9	23.68	+41.8	0.087
			1.0	272.23	Base	16.69	Base	0.061
			2.0	267.70	-1.7	3.10	-81.3	0.012
	0.25	0.25	0.5	359.91	+3.1	80.18	-21.3	0.222
			1.0	349.09	Base	101.82	Base	0.292
			2.0	329.28	-5.7	141.44	+39.0	0.43
	0.50	0.25	0.5	404.00	+8.6	194.00	-20.0	0.48
			1.0	371.94	Base	242.09	Base	0.65
			2.0	321.00	-13.7	318.50	+31.5	0.99
	1.0	0.25	0.5	392.91	+19.0	308.86	-20.3	0.79
			1.0	330.09	Base	387.39	Base	1.17
			2.0	250.12	-24.2	487.35	+25.8	1.94
	0.125	0	0.5	512.00	+41.0	288.00	-6.5	0.56
			1.0	492.31	Base	307.69	Base	0.63
			2.0	457.14	-7.2	342.86	+11.4	0.75
	0.25	0	0.5	492.31	-7.7	307.69	-10.3	0.63
			1.0	457.14	Base	342.86	Base	0.75
			2.0	400.00	-12.5	400.00	+16.7	1.00
	0.50	0	0.5	457.14	+14.3	342.86	-14.3	0.75
			1.0	400.00	Base	400.00	Base	1.00
			2.0	320.00	-20.0	480.00	+20.0	1.50
$m = \frac{SPAN}{2}$	1.0	0	0.5	400.00	+25.0	400.00	-16.7	1.00
			1.0	320.00	Base	480.00	Base	1.50
			2.0	228.57	-28.5	571.43	+19.0	2.00

Note: Percent Variations and Ratio M_C/M_D remain constant for frames having H/L, h/L and $h I_2/m I_1$ ratios shown; i.e., independent of span length.

and ridge-rise-to-column-height ratios. The moment distribution for the baseline condition, $I_2/I_1 = 1.0$ (constant section), is compared with the conditions when I_2/I_1 is respectively half and twice as great, As a further comparison, the ratio of midspan to haunch moment is given. It should be noted that this ratio and the percent variations will be constant for any frame having the geometry and cross sectional relationships shown regardless of span length of intensity of load.

The data of Table 10 indicates the percentage error resulting from the assumption of constant section is, in many cases, so small that it can be neglected. In many cases, in ridge roof buildings, where the ratio of crown to haunch moment is small, considerations other than crown moment dictate a member size with a section approaching the section size of the column. It should be noted that the relationship I_2/I_1, within the range normally used, has very little impact on moment distribution due to wind loads.

It is also assumed that the frame walls were not tied to the floor member in a manner capable of load transfer. To determine the impact of this assumption on frame moment distribution, the data of Table 11 was developed. A flat roof rigid frame loaded with a uniform unit vertical load was used to develop the relationships. The data shows that the percentage change in the moment distribution is small enough to be neglected and considering a tied rigid frame is not warranted.

As discussed previously, each rigid frame configuration will be compared to determine relative efficiency as a structural load transfer mechanism. This will be accomplished by analyzing each configuration for the three basic imposed loads: (1) uniform vertical downward load, (2) point load at any point on the roof surface, and (3) horizontal wind load perpendicular to the long axis of the structure. For this comparative analysis, unit loads will be used.

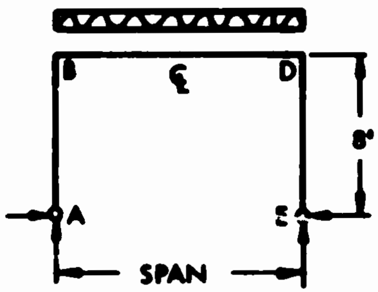
The design bending moment was determined for each configuration when acted upon by a uniformly distributed unit load acting downward. The results are shown in Figure 23. If the moments for the flat and ridge roof configurations are compared with the data of Figure 22, the improvement of these configurations as a structural transfer mechanism can be evaluated. For example, the circular arch is approximately 7.7 times more efficient than large span ridge roof configurations. The previous values were 12 and 6, respectively.

For each configuration the maximum design bending moment was also determined for the remaining two loading conditions; point load on the roof and horizontal wind load. The wind pressure coefficients on a structure are a function of the configuration. The wind pressure coefficients due to a 1 pound per square foot horizontal wind perpendicular to the long axis of the structures are shown in Table 12.

The results of the structural analysis for the three configurations (span length of 80 feet) and the three basic loading conditions are shown in Table 13. A review of this data reveals the relative efficiencies of each configuration as a load transfer mechanism. For example, the circular arch has an uplift of 30 pounds under the unit wind load. This load is 50 percent greater than the

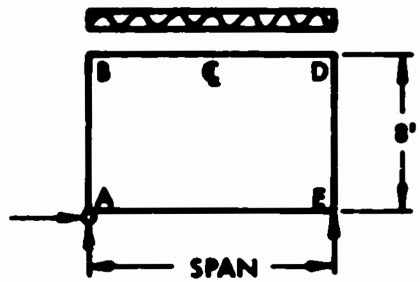
TABLE 11. IMPACT OF WALL/FLOOR LOAD TRANSFER ON MOMENT DISTRIBUTION

SPAN (FEET)	M_A & M_E			M_B & M_D			$M_{℄}$			V_A		V_E		H_A		H_E	
	TYPE		DEVIATION %	TYPE		DEVIATION %	TYPE		DEVIATION %	TYPE		TYPE		TYPE		CONFIG	
	I	II		I	II		I	II		I	II	I	II	I	II	I	II
80'	0	+15.64	NA	-497.28	-500.49	0.65	+302.72	+299.51	1.07	40.0	40.0	40.0	40.0	62.2	0	62.2	0
8'	0	+0.67	NA	-3.2	-3.33	4.06	+4.8	+4.67	2.78	4.0	4.0	4.0	4.0	0.4	0	0.4	0



CONFIGURATION TYPE I

SIMPLE FRAME



CONFIGURATION TYPE II

TIED FRAME

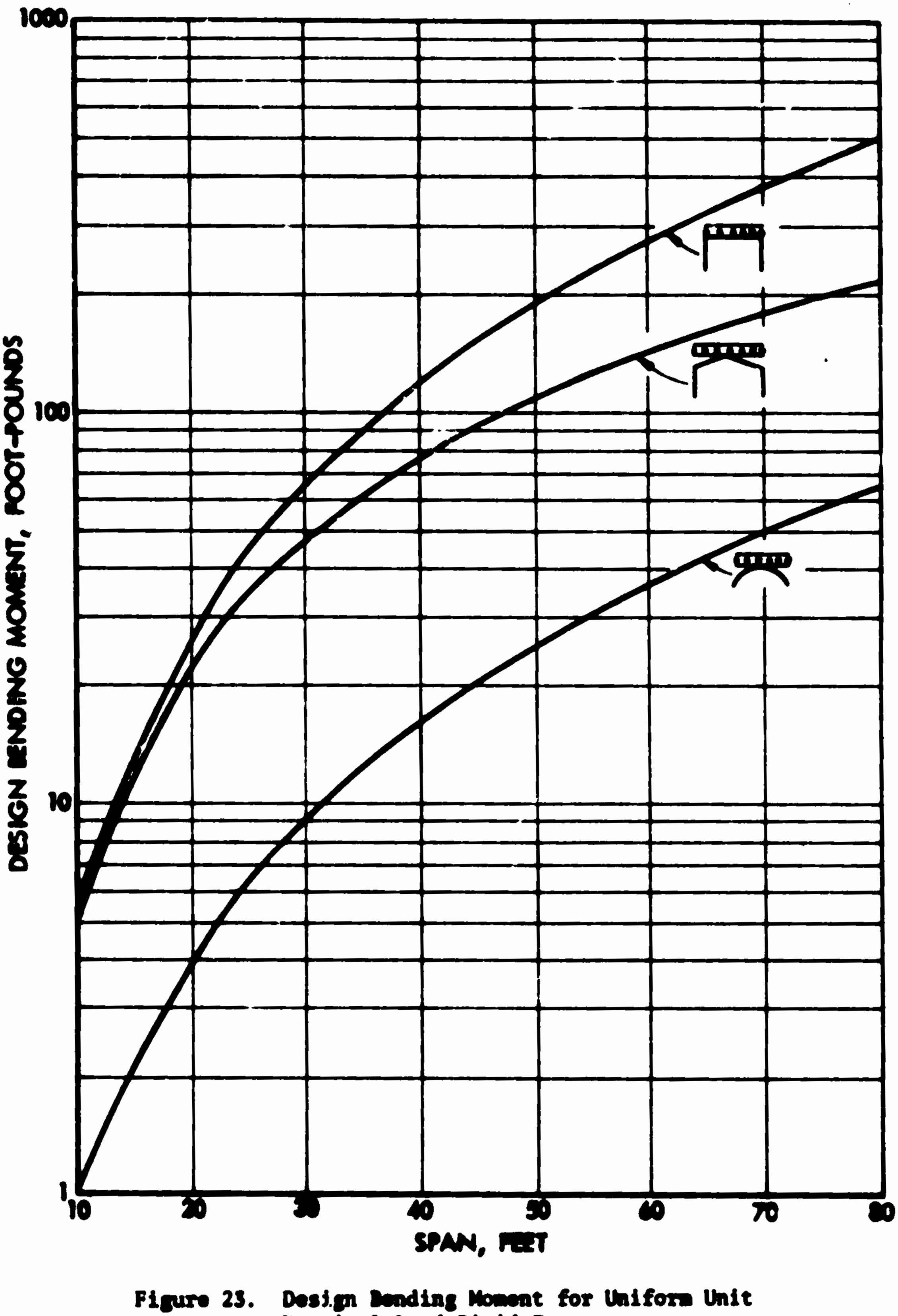


Figure 23. Design Bending Moment for Uniform Unit Vertical Load Rigid Frames

TABLE 12. WIND PRESSURE COEFFICIENTS AS FUNCTION OF STRUCTURAL CONFIGURATION

h/L	H:L:W	A	B	C	D	E	G	Remarks
0.10	1:1:1	0.9	-0.5	-0.6	-0.6	-0.7	-0.5	House
0.10	2.5:2:5	0.9	-0.5	-0.7	-0.7	-0.6	-0.5	
0.30	2.5:2:5	0.9	-0.5	-0.7	-0.7	-0.6	-0.5	
0.45	2.5:2:5	0.9	-0.5	-0.8	-0.8	[illegible]	-0.6	
0.10	1:4:4	0.9	-0.3	-0.4	-0.4	-0.8	-0.3	Closed Hall
0.30	1:8:16	0.8	-0.5	-0.5	-0.5	0.2	-0.6	
0	1:4:4	0.9	-0.3	-0.8	-0.8	-0.5	-0.5	Flat Roof
0	1:1:1	0.9	-0.5	-0.8	-0.8	-0.7	-0.7	
0	1:2.5: 2.5	0.9	-0.6	-0.8	-0.8	-0.8	-0.8	
0.1	-	0.15	-0.5	-0.6	-0.6	-0.8	-	Circular Arch
0.2	-	0.27	-0.5	-0.5	-0.7	-0.9	-	
0.3	-	0.42	-0.5	-0.8	-0.8	-1.0	-	
0.4	-	0.57	-0.5	-0.8	-0.8	-1.1	-	
0.5	-	0.70	-0.5	-0.8	-0.8	-1.2	-	

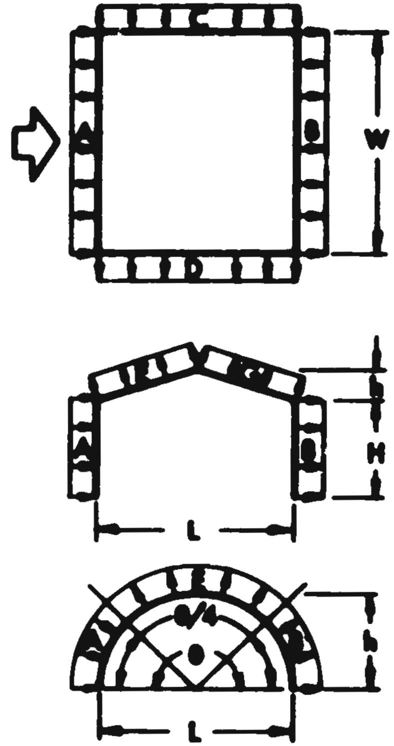


TABLE 13. DESIGN MOMENT AND REACTIONS - ONE PSF LOAD CONDITIONS, WIND - PERPENDICULAR TO LONG AXIS RIGID FRAMES

CONFIGURATION (80' SPAN)	WIND LOAD			UNIFORM VERTICAL ROOF LOAD			POINT VERTICAL ROOF LOAD			SUM OF MOMENTS (FT-LBS)
	MOMENT (FT-LBS)	H (LBS)	V (LBS)	MOMENT (FT-LBS)	H (LBS)	V (LBS)	MOMENT (FT-LBS)	H (LBS)	V (LBS)	
FLAT ROOF	268	38	20	497	62	40	10	1.2	1.0	775
RIDGE ROOF	133	20	21	217	27	40	7.3	0.5	1.0	357
CIRCULAR ARCH	165	36	30	65	26	40	9.7	0.5	1.0	240

equivalent load for the other two configurations and means that the tie-down requirements will be greater. The last column entitled "Sum of Moments" is not truly indicative of the final design bending moment for they have not been summed with regard to location of the individual moments. For example, the point load maximum moment occurs under the load while the uniform vertical load maximum moment occurs at the haunch. However, the sum will be used as being indicative of the relative efficiencies.

The relative costs of the structural frame can be determined by the data of Figure 24. The relationship between weight of material and section modulus shown in Figure 24 was determined from the most efficient wide flange section of each size. The lightest weight section was plotted against its elastic section modulus and the best fit curve drawn, and then normalized. To illustrate its use, assume the relative costs of the maximum design moments of Table 13 are to be determined. If the material to be used has an allowable stress of one, then the required section modulus would have the same numerical value as the moment. The flat roof configuration would require a section modulus 775/240 or 3.23 times larger than the circular arch. The ridge roof configuration would require a section modulus 375/240 or 1.49 times larger than the circular arch. Therefore, to achieve the required section modulus, from Figure 24 the flat roof uses 2.4 times more material and the ridge roof uses 1.3 times more material than does the arch, using standard sections for carrying a unit load.

4.6.2.4 <u>Material Requirements.</u>

The shelter configuration does not in itself impose a material requirement for the covering to function as a weather shield; however, there is a cost penalty imposed by commonality of use. For example, a shelter to be designed for barracks, mess hall or any other function that does not require a high roof at midspan would use the least material and cost the least to heat or cool with a flat roof configuration. If in order to have commonality a hangar of circular arch configuration and span of 80 feet was used as a mess hall, the initial cost penalty in materials would be 17 percent and the heating and cooling costs would also be increased by 17 percent.

The study results on material requirements using the covering as a thermal barrier indicate that both texture and surface of the outer covering impact the heating and cooling loads and hence the life cycle costs. Consideration should be given to a covering that varies with the climate (or perhaps a field-coating) in the deployment area. Coatings used for the cover kit would have high emissivity characteristics for use in the tropics and a different spray having absorptivity characteristics for use in the arctic. The fabric covering would be reversible. A field-coating would use the same characteristics.

The material selected for the load transfer function of Figure 20 can be selected from a variety of basic products with, of course, metals excluded. The previous structural analysis determines the physical and mechanical properties of the material selected. For example, the design criteria specifies

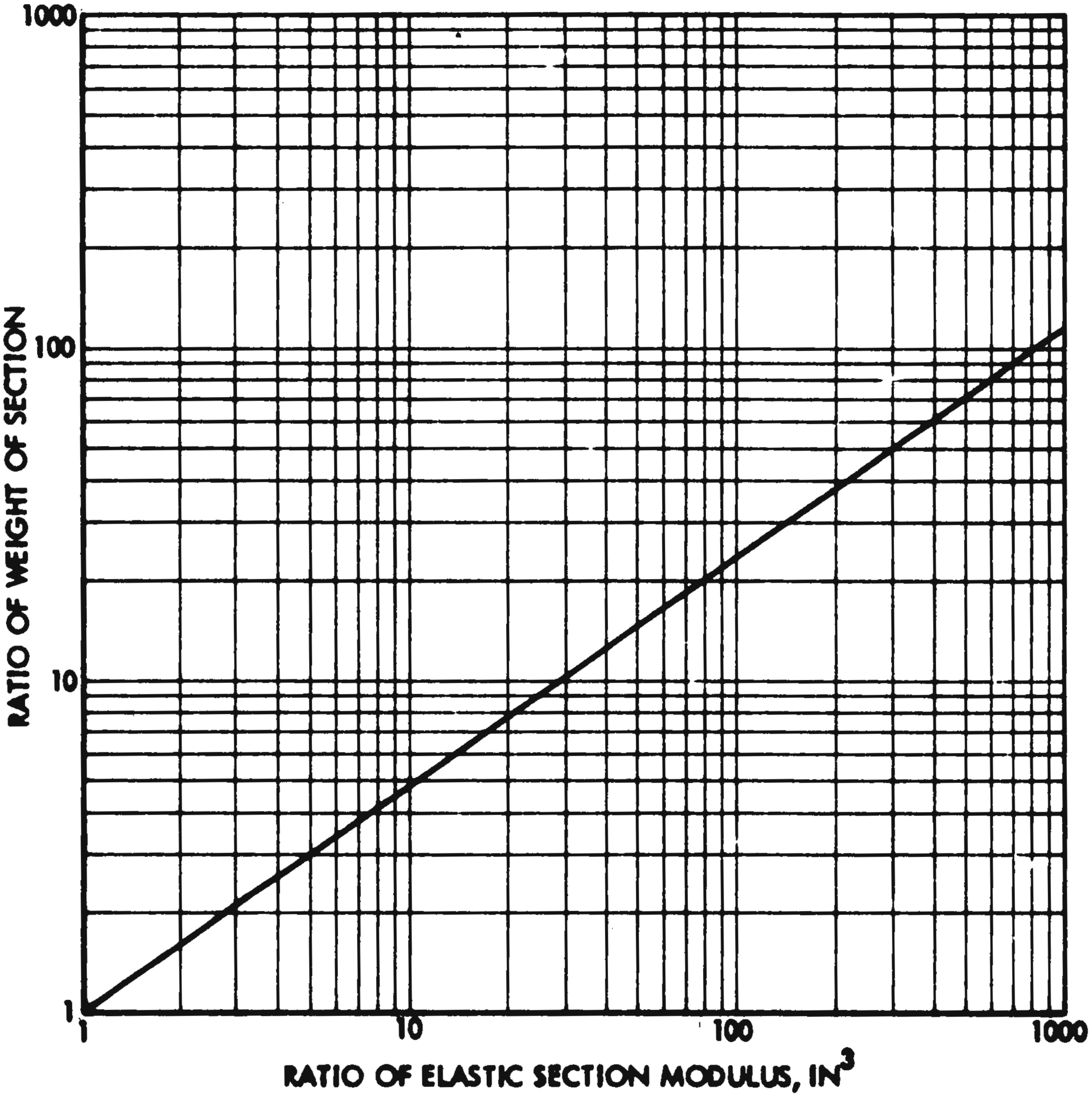


Figure 24. Weight of Rolled Section as Function of Elastic Section Modulus

90 knot gusts and a snow load of 40 pounds per square foot. The 90 knot gust can be considered equivalent to a steady state wind of 78 knots (89.82 miles per hour). The wind pressure would then be equal to:

$$p = 0.002556\ C_D V^2 \text{ in-lbs/sq ft}$$

where:

C_D = drag coefficient

V = wind velocity, mph

, then $p = 20.621\ C_D$ psf.

For purposes of determining material physical and mechanical properties, the requirements for a flat roof rigid frame will be used. The flat roof configuration was selected since it is the least efficient load transfer mechanism and hence imposes the greatest demand on the material properties. The data from Table 13 indicates that for a span of 80 feet, the bending moment will be:

Snow load = 497(40) = 19,880 foot-lbs
Wind load = 20.621(268) = 5,526 foot-lbs
Design Bending Moment = 25,406 foot-lbs

The usual design process would, at this time, select a specific material and divide the design bending moment by the allowable tensile stress to determine the section modulus of the structural member. The configuration of the structural member would thus be designed to furnish the required modulus at the least weight per linear foot. The configuration would then be examined for general stability of the section as well as for each compression element. For example, the member configuration is checked for:

- Slenderness ratio of compression elements
- Stiffened elements under compression
- Unstiffened elements under compression
- Web crippling

In addition to the stability of the element, the deflection under design load would be determined and compared to an established value that is usually expressed as some fraction of the span length.

Deflection or sag in a member is the result of a differential change in length between the upper and lower elements. The elements could be the faces of a rolled or extruded section of the members of a truss. It is generally accepted that in a spanning member under bending load the compression element shortens and the tension element elongates and the member now has a curvature or deflection. However, there are other mechanisms that cause deflections and, in general, they must be added to those resulting from the application of design loads. These mechanisms are, for example:

- Elastic strains
- Creep strains
- Shrinkage and moisture changes
- Temperature differentials
- Load Characteristics
- Form of structure; i.e., rigid frame or simple beam.

The design of durable and problem-free structures requires the acknowledgement that deflections will always occur and the maximum allowable is a function of the associated construction and intended use. The usual structure, such as a high rise steel or reinforced concrete building, is designed as a rigid structure and requires limits on deflections to insure that plastered ceilings do not crack, interior partition walls do not crack, that prefabricated exterior facings can be manufactured and installed to close tolerances, etc. The air mobility shelter concepts have a somewhat different set of requirements establishing the limits on deflection. Several of these requirements result from the fact that the air mobility shelter is composed of pre-fabricated components that are field assembled under an extreme temperature range. The air mobile shelter, designed as a flexible structure, would require, for example, the following restrictions on deflection:

- The function of the building not be impaired
- Sag of roof membranes shall not pond water
- Joints must remain watertight
- Mating surfaces of the components must match under the extreme temperature differentials
- Structural stability must not be altered.

The deflection, strength and environmental requirements jointly impose the physical and mechanical property requirements for the material selected. The resin systems show tensile yield strengths of from 4000 to 160,000 psi. Assume allowable tensile stress equal to 60 percent of yield; on this basis the section modulus required could vary from $\frac{25,406(12)}{4,000(0.6)} = 127 \text{ in}^3$ to $\frac{25,406(12)}{160,000(0.6)} = 3.18 \text{ in}^3$. This large range of section modulus required highlights the problem associated with high strength materials that do not also have an equivalent high modulus of elasticity. The modulus of elasticity for the two materials used in the above example are 3×10^5 psi and 54×10^5, respectively. The deflection of a member under bending load is inversely proportional to the moment of inertia and the modulus of elasticity. For purposes of illustrating the impact of tensile yield strength on deflection, it shall be assumed that deflection is inversely proportional to section modulus and modulus of elasticity.

On this basis the relative deflection of a member fabricated from these two materials would be $\frac{127 \times 3}{3.18(54)}$ or 2.22 to 1 with the higher strength material having the larger deflection. It therefore becomes apparent that to use the material at a high allowable stress either the modulus of elasticity must be raised proportionately or the configuration of the member must be designed to develop a large moment of inertia; the design becomes section limited.

It is therefore apparent that the optimum physical and mechanical properties would be:

- High tensile yield to minimize amount of material required
- Comparable high modulus of elasticity to limit deflection
- Low creep and elastic strains to minimize deflection.

The selected material will evolve to be a compromise between the desirable and the obtainable, in the time frame of interest. The member configuration will be used to control deflection and take advantage of the high strength to weight ratios obtainable with resin systems.

4.7 OTHER SHELTER CONCEPTS

Forecast advances in the general areas of fabrics and structural foams should allow foam-in-place buildings, and air-inflatable and framework-supported flexible-wall shelters, respectively, to achieve greater utility. Even with this added utility, primarily in the area of easy erection of large, lightweight structures, the basic lack of durability and environmental capability excludes these types of concepts from consideration for inclusion in a new "family" of shelters.

Nevertheless, several concepts of this type were examined to identify shelter-type uses for advancing fabric and structural foam technology. The concepts presented are:

1. Foam-in-place, air-inflatable form (reusable form; disposable shelter).
2. Circular arch tent (reusable).
3. Field-rigidized air-erected shelter.
4. Field-foamed panel shelter.

These concepts might have some application in the expedient, short-term deployment environment. Functional applications would be for missions such as:

1. Temperate-climate temporary hangar or general storage.
2. Temporary billets.

The four concepts are described in the following paragraphs.

4.7.1 Foam-in-Place Using Inflatable Reusable Form

A reusable inflatable bag is used as the form for a spray-on foam. The shape of the shelter can be any configuration. The bag can be manufactured to any cross-sectional configuration, and the configuration is maintained when internally pressurized by the use of restraining ribs in an egg crate pattern as shown in Figure 25.

The configuration is controlled by stiffening ribs, which, in turn, determine the spacing of the sculptured texture of the ceiling. This textured surface, in addition to being esthetically pleasing, can act as an acoustical baffle.

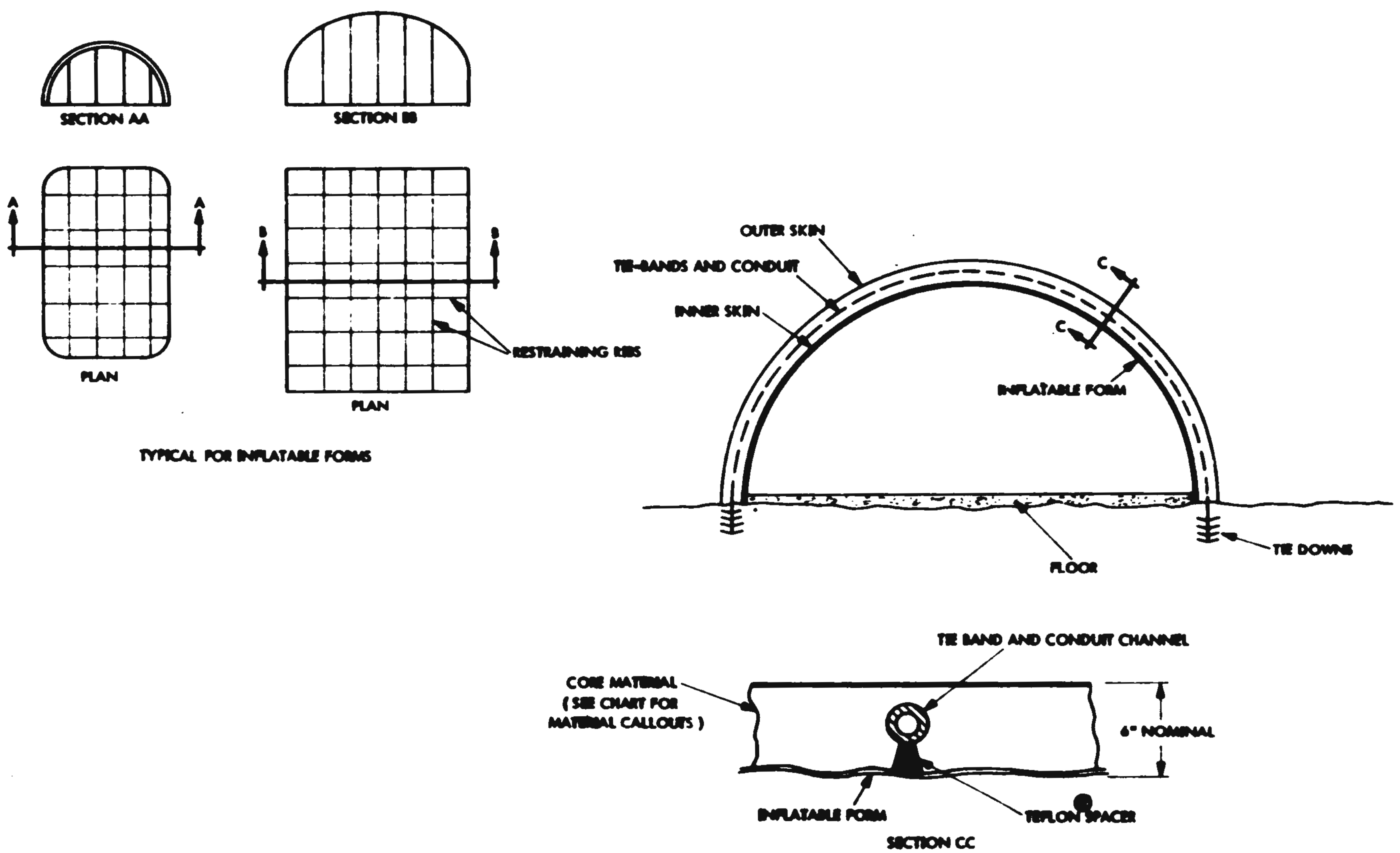


Figure 25. Foam in Place-Using Reusable Inflatable Form

The restraining ribs are perforated to permit the free passage of the inflating agent from one cell to another. The bags are manufactured in modular lengths and are connected to provide any length structure by fasteners such as Velcro®. The same type fasteners are used to connect the end walls.

The hollow aramid/resin system tie-bands and teflon spacers shown in the figure are multi-functional. They are used to help shape the form, tie down the shelter and act as conduits for either the electrical or environmental distribution systems. Section C-C is a typical section through the shelter and shows the Teflon® spacers that can be removed and replaced by electrical fixtures when the tie bands are used as electrical conduits. Table 14 provides a tabulation of the potential materials of construction.

4.7.2 Circular Arch Tent

The concept, which consists of a series of pairs of stabilized arches covered by fabric, is expandable, by the addition of modular elements consisting of pairs of arches, fabric and sill plates.

The concept, as fabricated from the materials listed in the table shown on Figure 26, is light weight, on the order of 50 pounds per linear foot (deployed) and is readily transportable and compatible with ISO standards.

It is estimated that a 30 by 48-foot (erected size) shelter will have a stowed volume of 60 cubic feet, including necessary erection equipment. The size of the shipping container would be 2 by 3 by 10 feet. This concept has a deployed/stowed expansion ratio in excess of 100:1 for a 30 by 48-foot shelter and can be further expanded by the addition of pairs of arches and fabric (modular elements).

The covering fabric is designed to provide a thermal barrier through the utilization of specific material thermal radiation characteristics and is reversible to allow flexibility in use under various environmental conditions.

The configurations selected for the structural elements of this concept are amenable to mass production techniques. As an example, the covering fabric (40 ounces per square yard) can be continuously woven on existing production looms with the thermal control coatings applied as a secondary operation.

The structural arch members are short, straight tubes having a constant section and diameter, which allows for simple tooling and size control. The fibers selected for these members are compatible with each other and the selected resin system. Although these tubular members cannot be produced as a continuous part, they can be economically "batch" produced. These straight tubular parts have sufficient flexibility to be bent during assembly to form the structural arches. Because these arch members are hollow throughout their length, they can be used to carry organic utilities such as power distribution networks, as well as heating and cooling ducts.

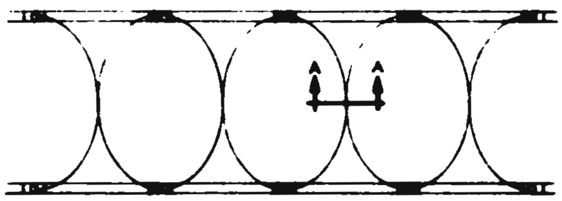
The deployment of this shelter concept is simple and consists of the following steps:

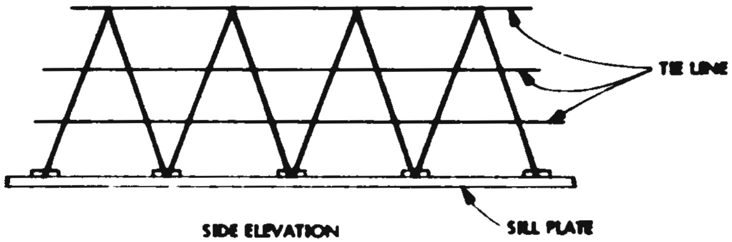
- Placement, leveling and anchoring of sill plates.

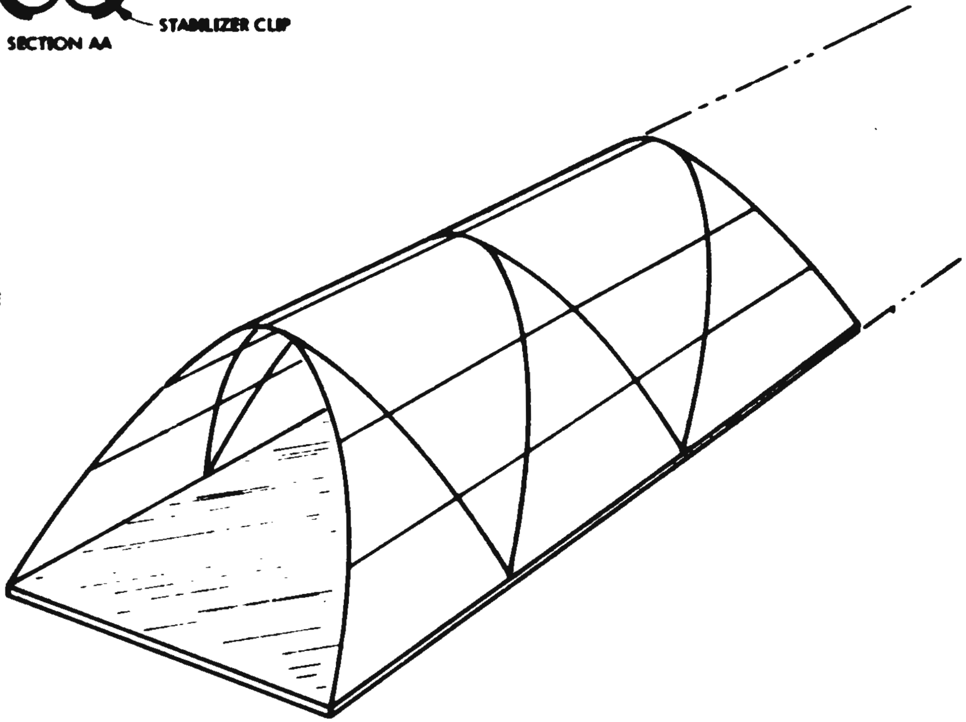
TABLE 14. FOAM-IN-PLACE SHELTER MATERIALS

MATERIALS

AIR-INFLATABLE FORM	INNER SKIN	TIE BANDS	CORE		OUTER SKIN	FLOOR
Teflon®		Resin Systems:	Foams:			
CTFE		● Aramids	A. Rigid (structural, integral skin type)			Epoxy-filled*
Nylon		● Polyesters		density		Polyester-filled*
			● ABS	$50\#/ft^3$		Polyurethane-filled*
			● Polycarbonate	$50\#/ft^3$	none required	
			● Noryl	50		
			● Polystyrene	43.5		
			B. Rigid (no surface skin)			
			● ABS	31	Epoxy	*The filler can be any readily available indigenous organic or inorganic bulk material.
			● Cellulose Acetate	6-8	Polyester	
			● Epoxy	5-8	Urethane	
			● Synthetic Epoxy	36-42		
			● Phenolic	2-4		
			● Urethane	2-25		
			C. Flexible			
			● Silicone	10	Silicone	
			● Polyurethane	1.5-5.0	Polyurethane	







MATERIALS					
ARCHES	FABRIC	CLIPS	TIE LINE	SILL PLATE	FLOOR
ARAMID - REFRACTORY OXIDE FIBER/ EPOXY TUBULAR LAMINATE	WOVEN ARAMID FABRIC	EXTRUDED FIBER FILLED NYLON	ARAMID	COMPRESSION MOLDED FIBERGLASS/ EPOXY LAMINATE	"FOAM-IN-PLACE" 80 PSF POLYURETHANE
FIBERGLASS/ EPOXY TUBULAR LAMINATE	WOVEN FIBERGLASS FABRIC	EXTRUDED FIBER FILLED POLY-CARBONATE	NYLON		POLYVINYL CHLORIDE MAT

Figure 26. Circular Arch Tent

- Assembly and erection of the segmented arches
- Connection of organic utilities
- Placement of covering fabric. Tie lines may be used to provide support to the fabric on longer spans between the arches.
- If flooring is required, it can be a "foam-in-place" 80 lb/cu ft urethane foam using indigenous material as filler, plastic matting, etc.

The disassembly procedure is the reverse of the above.

This shelter concept can be modified to increase its resistance to intrusion by impregnation of the covering fabric by the spray application, after erection, of an ambient-temperature curing resin system such as polyester.

4.7.3 Universal Field-Foamed Panel Shelter

The use of one basic panel which can be used to develop the configuration of any of the shelters required and which can be easily tailored by the application of materials to provide short or long term shelters, as well as shelters which are suitable for extremes in environment, deserves consideration.

The concept is developed as follows: 1/4-inch-thick Kevlar® honeycomb sheets are formed into pans (or panels) that are 8-feet-wide by 16-feet-long with 3-inch-thick sides, as shown on Figure 27. These panels have edge connections that provide for joining of additional panels to any of the four panel edges. These connections can be separate moldings or extrusions, or hinges as shown on the figure. Adhesive coated pads of reinforced materials could also be applied in the field to connect the panels. The pans are designed to be "nested" during transportation into a nominal 8 x 8 x 20-foot ISO container. A space 8 x 8 x 4 feet forming one end of the container is reserved for storage of foaming materials, hinges, and utility ducts. One ISO container can carry 48 of these pans in the nested configuration.

The basic panel is used in the field to form floor, wall and roof elements of shelters. These elements are formed by foaming insulating and structural material into the pans. Figure 27 indicates the arrangement of pans considered to provide shelters for moderate, tropic and arctic climates, as well as modifications for floor panels and the provisions of organic utilities.

4.7.4 Field-Rigidized, Air-Erected Shelter

This concept was developed to demonstrate the use of materials that could be sprayed on a form and field-cured to provide stability and rigidity.

The concept includes an inflatable bag or bladder which is stored in an 8 x 8 x 20-foot ISO container. The container is designed to provide a central core and fold-out floor panels. This concept is illustrated in Figure 28.

After setting of the container on level ground, the fold-out panels are extended and the B-staged reinforced polyester bladder is extended by air pressure. A spray-on hardener is then used to coat the fabric. The central core provides for ventilation, light, and organic utilities.

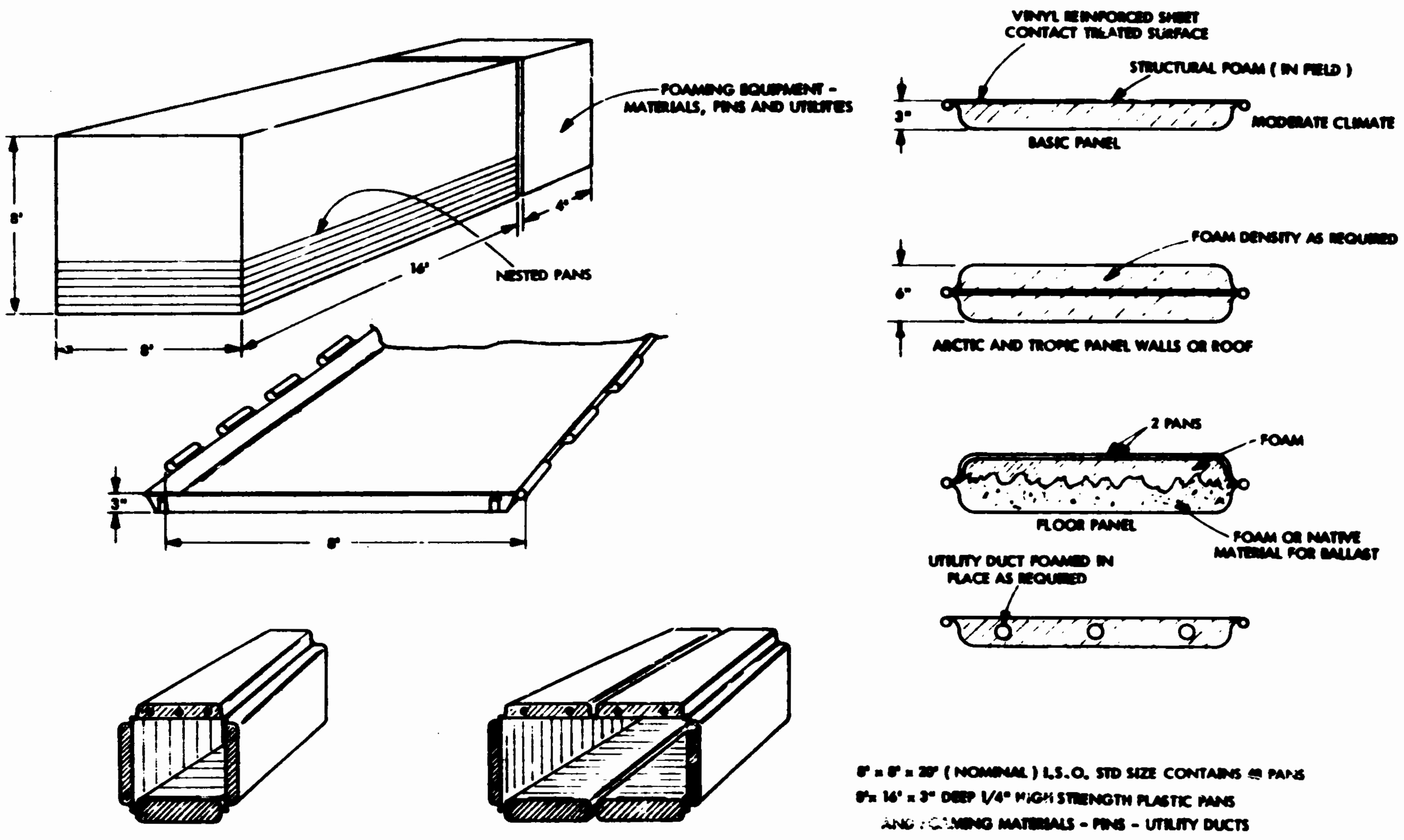


Figure 27. Universal Field Panels

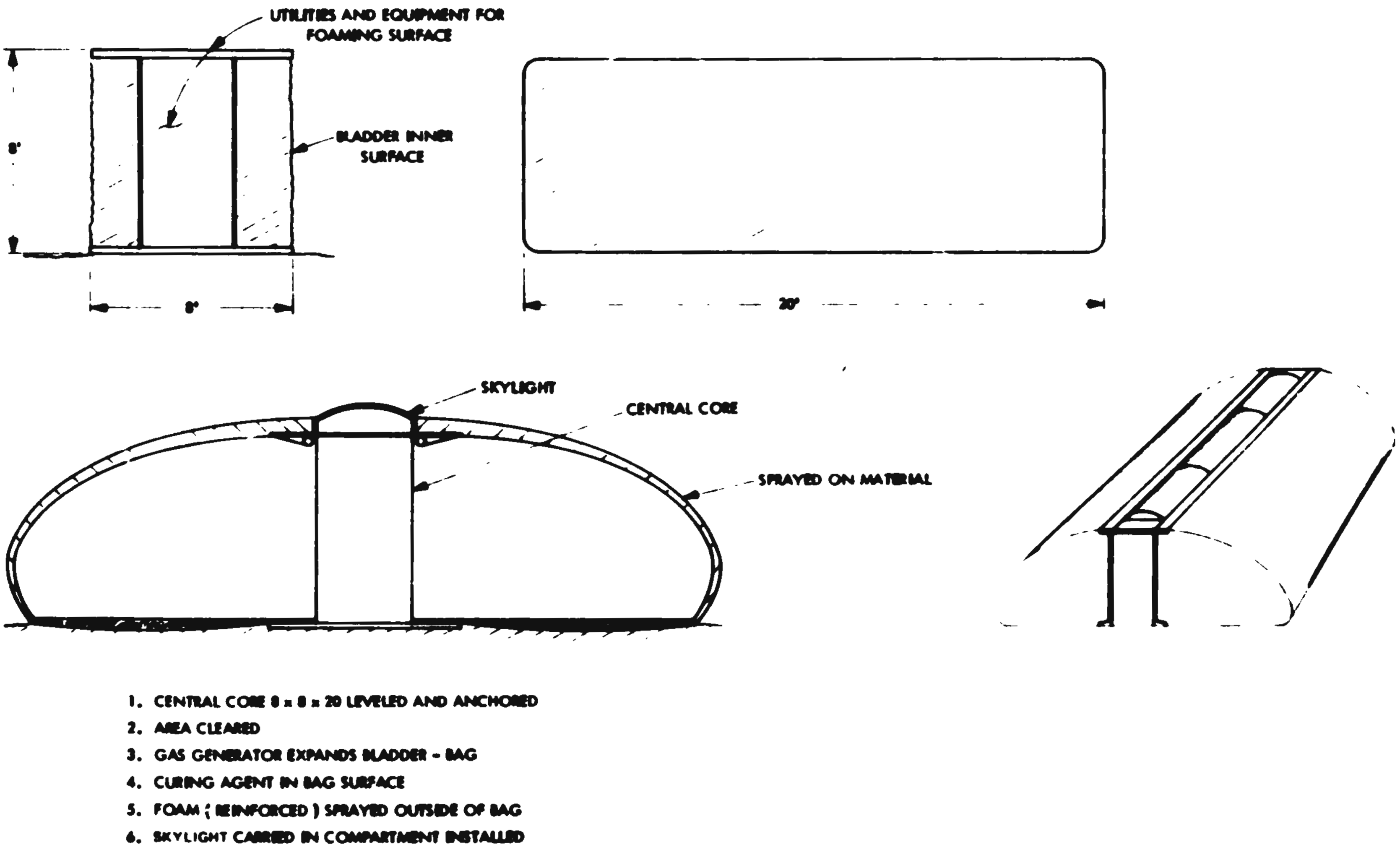


Figure 28. Field-Rigidized, Air-Erected Shelter

SECTION V
MATERIALS AND PROCESSES

5.1 INTRODUCTION

This section presents a discussion of the materials and processes recommended for application to either a new family of air mobile shelters, or redesigned versions of existing shelters.

The review and evaluation of existing shelters (Sections II and III), and the configuration and makeup of the advanced shelter concepts (Section IV), individually dictate the common set of material and process requirements to achieve the performance required of the 1980's air mobile shelters. The material and process requirements are categorized as follows:

1. Basic structural requirements
2. Basic non-structural requirements
3. Basic manufacturing requirements.

Each of these requirements is individually discussed in the following subsections. It should be realized, however, that all three types of material requirements are interrelated to some degree. For example, successful adhesive bonding requires that the material be compatible with the bonding temperature and pressure (a manufacturing requirement) in addition to having similar coefficients of thermal expansion to the face sheet (a non-structural requirement) and a strength consistent with structural requirements. The combination of all these requirements determines the material properties necessary for shelter construction.

Following the requirements discussion, the rationale for forecasting the availability of necessary materials properties is presented.

This section then presents an array and discussion of candidate material systems recommended for use in the shelter concepts. Many example material applications were presented with the concepts in Section IV.

5.2 BASIC STRUCTURAL REQUIREMENTS FOR MATERIALS

The basic structural requirements approach for materials that is necessary to achieve improved shelter performance is twofold, as concluded in Section III:

1. Use more conservative design allowables on all structural properties, and supplementary kits, to achieve more strength, rigidity, and damage-resistance in high expansion ratio shelters operating in severe conditions.
2. "Recapture" the added weight resulting from the larger structural element sections and added equipment by using materials with higher weight-specific properties.

Specifically, the materials selected are required to be superior to aluminum and laminated, oriented-ply fiberglass/epoxy, and approach the capability of continuous fiber reinforced epoxies such as high modulus graphite fiber epoxy currently used on aircraft. The properties that must be improved are:

1. Specific flexure, tension, and compression modulus of elasticity.
2. Specific tensile yield, compression ultimate, and shear ultimate strength.
3. Specific impact resistance, any test method, over temperature range of 0° to $+125^{\circ}F$.
4. Lower coefficient of thermal expansion.
5. Lower creep under load.
6. Higher hardness in manufactured form.

It is re-emphasized that for the most part, the structural property improvements are on a weight-specific basis. Weight saving is the goal. As is emphasized in Reference 54, many panels and joints in container and shelter design should be designed to be relatively flexible, or even elastic. (Reference 54 is recommended as a particularly comprehensive and useful analysis and general treatise on selecting optimum combinations of materials for military containers and shelters.) The currently open material options to achieve the above listed material properties improvements are generally in the area of high-cost-per-pound materials, relative to aluminum.

5.3 BASIC NON-STRUCTURAL REQUIREMENTS FOR MATERIALS

The basic non-structural requirements approach for materials that is necessary to achieve improved shelter performance parallels that for structural requirements:

1. Use more conservative assumptions regarding material durability, aging resistance, and general environmental resistance; this will often result in use of thicker coatings, extra covers, etc.
2. "Recapture" the added weight implicit in this approach by using premium grade materials that are lighter in relation to the properties required.

In addition, there are certain explicit non-structural property requirements stated in the Statement of Work for the Air Mobility Shelter Conceptual Study RFP. Tables 4 and 7 list the property requirements of interest, which are repeated here for convenience:

1. Electrically nonconductive (per RFQ Statement of Work)
2. Noncorrosive
3. Lower thermal conductivity than the material being replaced
4. Noncombustible
5. Nontoxic, including during exposure to direct flame
6. Inert to a wide range of solvents
7. Lower moisture absorption than epoxies currently used in fiberglass layups
8. Near-zero shrinkage from heat or aging
9. More stable strength, stiffness, and hardness characteristics over a -50° to $+125^{\circ}F$ temperature range than current fiberglass/epoxy layups

10. UV resistant compared to fiberglass/epoxy layups with any current UV stabilization additive
11. Will not support fungus or bacteria; nonedible.

Achievement of these goals with materials applicable to shelters from a structural or manufacturing standpoint will contribute largely and directly to meeting the advanced-shelter goals of Table 7.

5.4 BASIC MANUFACTURING REQUIREMENTS FOR MATERIALS

The basic manufacturing-requirements approach for materials that is necessary to achieve the structural, non-structural, and cost requirements for improved shelter system performance is as follows:

1. The material must be amenable to forming or otherwise fabricating into large, integrally-stiffened panels or other forms, with as many fittings as possible and other detail features formed-in, to reduce secondary operations.
2. The material must be amenable to recently-developed, low-cost, reliable, automated or machine-aided manufacturing and inspection methods.

The manufacturing methods considered are:

1. Compression molding of machine-layup oriented or chopped fiber laminates.
2. Pultrusion of the same types of reinforced plastics as for Item 1.
3. Injection molding or casting of filled plastics, with high-performance fillers.
4. Machine-aided layup or winding of oriented-fiber-reinforced epoxies or other plastic matrix, from prepreg tape or broadgoods.
5. 3-D, closed-cell weaving of high-performance-fiber/plastic-prepregged filament.
6. Controlled-density foaming of filled, closed-cell foams.
7. Large-scale sprayup with filled coatings.
8. Co-curing of multiple parts (i.e.; core, face sheets, fillings, and coatings).
9. Rapid, low-pressure cure techniques such as UV-cure, low-temperature cure, microwave cure, and resistance cure . . . each of these cure methods can be precisely controlled and generally only requires low-cost tooling (compared to autoclave or heated-press cure).
10. Machine-assisted, reliable inspection techniques based on such developing approaches as ion-graphing, acoustical holography, radiation techniques, and improved acoustical techniques.

The following subsection presents the rationale forecasting the availability of materials meeting the above requirements, and the availability of the suggested manufacturing/inspection methods.

5.5 FORECASTING MATERIAL AVAILABILITY

The problem involved in selecting future materials for application to future shelter designs has two separate elements:

1. Forecasting the level of improvement in properties that might be achieved.
2. Forecasting the availability of the material on a commercial basis during the time-frame of interest.

In order to provide credible and near-term useful recommendations in both of the above-listed forecasting areas, a broad range of developing material systems was reviewed beginning in Study Phase I by scanning technical and trade journals, technical reports, and materials-related company brochures and publicity releases. Simultaneously, the physical-property improvements required for advanced shelters emerged, as presented in Sections II and III.

As a result of comparing the Phase I material-properties review results with the shelter evaluation results, it was concluded that no particular improvement in material properties was required, if pilot-production or laboratory-available properties were considered. In other words, no "forecast" of properties improvement was required. Instead, the availability of the materials on a commercial basis during the 1980's was the problem.

The basis of forecasting commercial availability was to eliminate from consideration any advanced material for which a specific, large, non-shelter use (or uses) could not be found in the reference material reviewed. In other words, the economic impetus to bring laboratory materials to the market had to be present.

In summary, therefore, all recommended material systems and processes noted in this report as applicable to shelters are:

1. Available today, as regards demonstrated properties, including manufacturability.
2. Are already being developed for a large, near-term market.

Therefore, the only "forecast" required is of whether or not the commercial availability will be in the late 1970's and early 1980's. It is submitted that materials already in the laboratory or pilot production by the mid-1970's have sufficient lead time for being brought into widespread use in 5 more years. This conclusion is based on the similar timely progress of materials like Kevlar®, high-density polyurethane structural foam, pultruded fiberglass, polycarbonates, Teflon®, ultra-high-molecular weight polyethylene, and others.

The specific physical properties and process descriptions presented in the following discussions are supported by the References in this report, and many similar confirming but less notable sources.

5.6 MATERIALS AND PROCESSES SELECTED FOR SHELTER APPLICATION - SUMMARY

This subsection presents a summary evaluation of the materials and processes selected for shelter applications. All possible material combinations are not shown. Because of the burgeoning diversity of available material variations, only notable or typical examples are shown.

The following are (1) a list of recommended resins for use as the matrices for molded, pultruded, or laminated composites or individually as coatings or molded fittings; (2) a list of reinforcing fibers or fillers, for use as oriented-ply reinforcements, fabrics, or chopped fillers; and (3) a list of foams for use in structural applications or insulation applications:

1. <u>Resins</u>
   a. Epoxies
   b. Phenolics
   c. Polycarbonates
   d. Laminated, oriented-fiber/resin with integral stiffeners, co-cured with fittings.
   e. Closed-section (integral-stiffeners) pultruded continuous-fiber/plastic composite
2. <u>Fittings and Small Beams or Panels</u>
   a. Compression-molded, chopped fiber or whisker-filled resin
   b. Cast, chopped-fiber or whisker-filled resin
   c. Machined, fiber-filled resin pultruded standard sections
   d. Co-cured, wet-layup, oriented-continuous-fiber/resin fittings integral to panels.
3. <u>Insulation and Coatings</u>
   a. Polyurethane foamed insulation
   b. Filled elastomer (filler dependent on property required), sprayed on
   c. Urethane, sprayed on
   d. Epoxy, sprayed on
   e. Polyvinyl, hard skin or sprayed on.

The following subsection presents an analysis and discussion of these recommended materials, comparing them to current materials, where required, to illustrate the relative benefits.

5.7 MATERIALS-SELECTION ANALYSIS

The first step in identifying the materials and processes for the 1980 time period was based on an in-depth review of the materials and processes used in existing shelters. Section II of this report covers this subject, and Table 3 in that section lists all the materials presently used in air mobile shelters. These materials are considered to be less than 1970 state-of-the-art and, in general, are not considered to be candidate materials for future advanced shelter concepts, even though the generic categories <u>are</u> recommended, as noted in the previous subsection. In the last 5 years, great strides have been made in the development, application and modifications of current shelter materials, which can then be used for advanced shelter concepts. The major advances in today's materials have been in the improvements in material properties, and in the design of composites or material systems to take advantage of specific material properties.

For this discussion the material requirements imposed by the deficiencies or problems associated with existing shelter concepts (see Section III) can be considered operational requirements.

5.7.1 Filled and Unfilled Resins

The generic families of plastics, both filled and unfilled, meet all the non-structural operational requirements as shown in Table 15.

An example of the operational requirements dictating material properties, i.e., limiting the number of potential material candidates, is shown in Figure 29. The climatic extremes impose a temperature swing of 175°F. If a honeycomb panel is to be designed with an aluminum face sheet and bond line failure is to be avoided, the compatibility of thermal expansion coefficients must be considered. Otherwise, the bond line failure results from the build-up of shear stresses along the bond line and is attributed to differential thermal expansion or contraction. As a frame of reference, the value for aluminum sheet has been shown in Figure 29. If bond line failure is to be avoided, then, from Figure 29, only six plastic materials can be used as honeycomb, adhesives or fillers.

There is as great a diversity of structural property values among plastics as among metals. This diversity has greater significance for the unfilled plastics than for those which contain fillers, or reinforcement, of glass, mineral, fiber, or mixed with other resins. Filled or reinforced plastics are a major consideration of this report.

Unlike metals, the mechanical properties such as tensile ultimate, tensile yield, impact and fatigue of unfilled plastics decrease with increasing temperature. For the design of shelters, this loss of mechanical properties is not considered to be critical. In addition, the mechanical properties of the unfilled plastics vary over a considerable range of values. Examples of these wide range of properties are shown in Figures 29 and 30. It is for these reasons that reinforcement and other fillers are added to basic plastic formulations to develop the material design which tailors the properties to meet specific material application.

5.7.2 Foams

The available physical and mechanical properties of selected foam materials are shown in Table 16.

A general discussion of several specific foam materials is developed in a later part of this section.

5.7.3 Fibers

A family of materials called aramids was introduced commercially in 1972 and will contribute to the basic composite structures of rigid and flexible wall shelters. The application of this material is based on the present status of product development and the availability of the basic polymer.

TABLE 15. NON-STRUCTURAL OPERATIONAL REQUIREMENTS OF SELECTED MATERIALS

Material	Electrically Nonconductive	Noncorrosive	Shall not Support Combustion	10-Year Storage Life	Inherent Chemical/ Biological Protection	Inert to Solvents	Low Moisture Absorption	Low Shrinkage Coefficient	Weatherability	Remarks
Refractory Oxide Fiber Reinforced Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Refractory Oxide and Graphite Fiber Reinforced Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Aramid (Kevlar®49) Fiber Reinforced Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Kevlar®49 Fiber and Refractory Oxide Fiber Reinforced Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Kevlar®49 Fiber Woven Fabric	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Refractory Oxide Fabric Woven Fabric	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Kevlar®49 and Refractory Oxide Fibers Woven Fabric	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Chopped Fiber Filled Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Polycarbonate Resin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Polyvinyl Chloride	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	(1)
ABS	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	(2)
Polybutadiene	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Polyurethane-Modified	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Polycarbonates-Modified Fiberglass	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Organic Fibers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Refractory Oxide Fibers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Rigid Foams	Yes	Yes	No	No	Yes	No	No	Yes	Yes	(3)

(1) Improvements to solvent attack under study for use in 1980's.
(2) Improvements underway to minimize solvent attack.
(3) Foams may be tailored for the 1980's to minimize shortcomings.

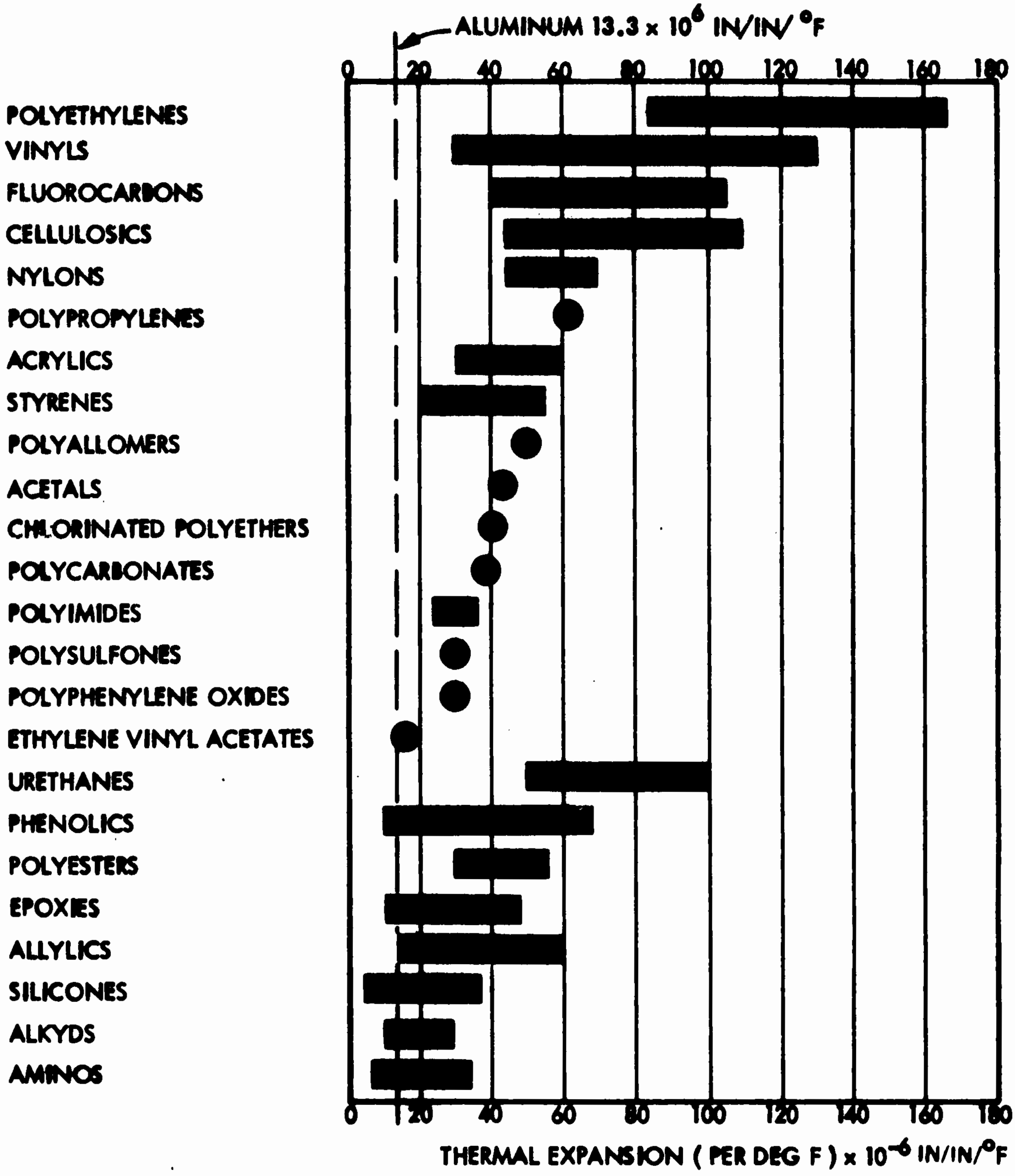


Figure 29. Coefficient of Thermal Expansion for Selected Resins

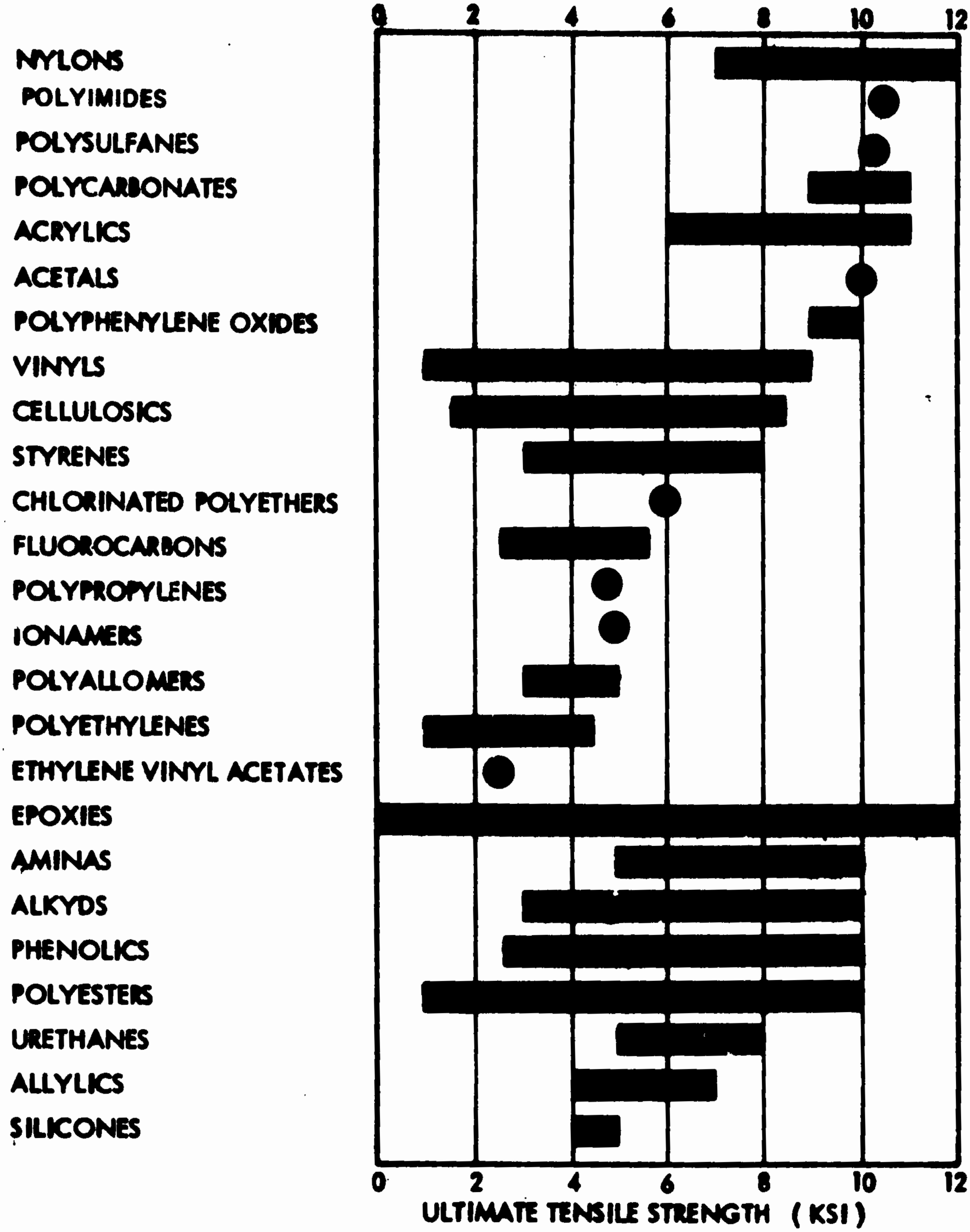


Figure 30. Ultimate Tensile Strength of Selected Resins

TABLE 16. PHYSICAL/MECHANICAL PROPERTIES OF SELECTED MATERIALS

Material	Tensile				Compression		Flexural		Thermal					Usable Temperature Range °F		Shear	
	Ultimate ksi	Yield ksi	Elongation %	Modulus 10^5 psi	Yield ksi	Modulus 10^5 ksi	Stress ksi	Modulus 10^5 ksi	Conductivity Btu/SF(in)(hr)(°F)	Expansion 10^{-6} in/in/°F	Impact Resistance Ft-lbs	Density pcf	Creep (1) %	Low	High	Longitudinal ksi	Transverse ksi
Aramid Fabric (Estimated)	125	100	25	190	-	-	-	-	-	-	-	50	5	-	450	-	-
Aramid + Refractory Oxide/Epoxy Laminate	160	140	3	120	140	120	-	-	-	-2.	-	84	6	-	300	(	100
Aramid "Rope"	300	200	30	190	-	-	-	-	-	-	-	85	-	-	350	-	-
Fiberglass Filled Polycarbonate Extrusion	21.5	13	3	17	19	17	19	13	-	0.2	45	94	-	-	295	-	-
Polyimides Resin Family & Chopped Glass (65%)	28	21	1	45	42	-	56	38.4	3.59	0.8	17	119	-	-	500	-	-
Urethane + Glass Reinforced	6	5	20	3	2.5	-	-	0.8	-	0.15	10	88	-	-	200	-	-
Polyester + Woven Glass Cloth	50	35	1	-	19	-	75	3	1.2	-	10	120	-	-	300	-	-
Urethane Foam (Flex)	0.03	-	300	-	0.04	-	-	-	-	-	-	2.0	-	-	150	-	-
Urethane (Rigid)	3	-	6	1.6	0.04	0.3	7	1.7	0.6	3.	10	40	-	-	150	·	-
Phenolic + Glass Injection Molded	8.5	-	-	17	30	-	14.5	-	-	-	0.4	95	-	-	300	-	-
Phenylene Oxide (Noryl) + Glass Fiber Reinforced	17	14	6	13	17.2	-	22	10	1.1	0.2	2.3	76	-	-	250	-	-
Structural Foam (Polystyrene)	3.5	-	-	-	-	-	.2	2.7	-	0.5	-	44	-	-	190	-	-

(1) 80 ksi for 1000 hours

This fibrous class of the material will probably find direct application as a reinforcing material for composite structural configurations. The aramids can be used in the same manner as glass, graphite or boron fibers, which are also recommended for application to shelters. The two aramids of interest to future shelter studies are Kevlar® and Nomex®. This family of materials is resistant to the various solvents that could be encountered during deployment. Kevlar® is limited by a compressive strength that is not as high as other fibers; however, if this physical property is necessary, a blend of graphite refractory oxide or boron fibers within a selected resin matrix can be used to increase the compressive strength.

Unlike other organic fibers, such as Nomex®, the stress/strain curve to failure is linear and is similar to that of glass and other inorganics, see Figure 31. The tensile strength of the aramid is excellent when compared to other reinforcing fibers, as shown in Figure 32, and indicates a maximum theoretical tensile strength of 600 ksi, which is also relatively insensitive to fiber aspect ratio.

The data of Figure 33 indicates the potential of the aramids in conjunction with plastic composites where strength and stiffness to weight are of importance. A further comparison of the high degree of material potential that exists to the aramids as structural members for the 1980 shelters is presented in Table 17 which compares the properties of aramids with that of glass and graphite in a unidirectional laminate.

Presently, the machining of the aramid fiber in a laminate panel is quite difficult. The aramid is tough (not like glass), and therefore it tends to yield rather than break, thereby resulting in a poorly machined finish.

As a support member (rods or frame ribs) or tie-down cable, its potential use appears to be unlimited.

5.7.4 Composites-systems

Glass filaments in epoxy resins are considered the grandfather of composite materials. Glass theoretically is an extremely strong material and current research is producing glasses that achieve much of this theoretical strength. S-glass, with a modulus of 12.5 million psi and a tensile strength of 600,000 psi, now is in common use in advanced composites. An even newer glass filament material developed by the Air Force, 970-S, has a tensile strength of 800,000 psi and a modulus of more than 15 million psi. Recently 11 glass compositions with modulus values over 20 million psi and another 24 in the 18 to 20 million psi range have been developed.

The vast majority of research and development has centered on polymer matrices. Metal matrices are distinctive by their absence and only a little effort has been expended on ceramic matrices. Polymer matrices have included almost every material available--from acetals and epoxies to polyesters and polyimides. Most of the specialized applications use an epoxy resin matrix. Glass composites that are available today exhibit relatively poor strength characteristics in compression. Manufacturing techniques such as crossed-ply filament winding of composites can be used to improve the compressive

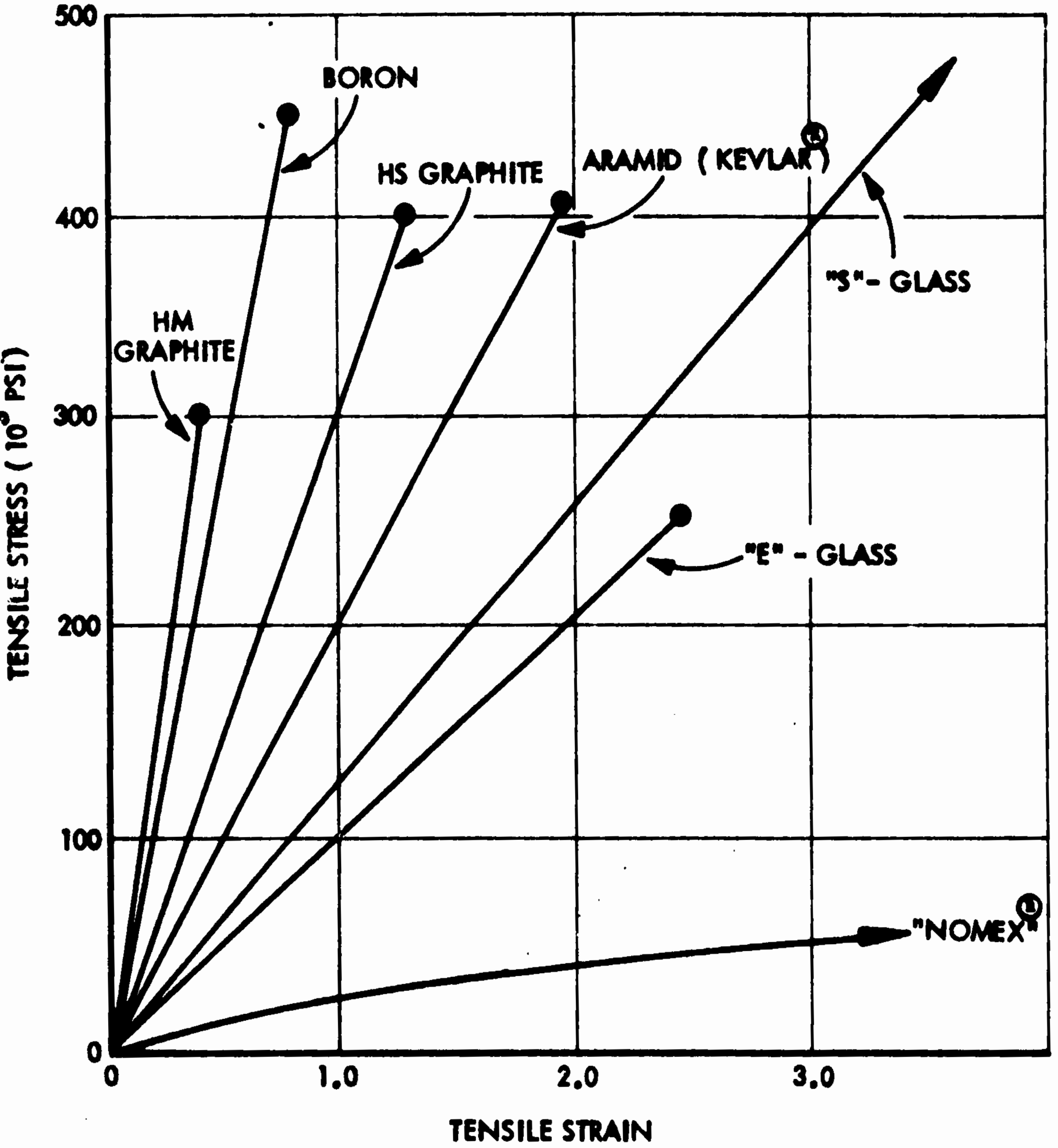


Figure 31. Stress/Strain Curves of Various Fibers

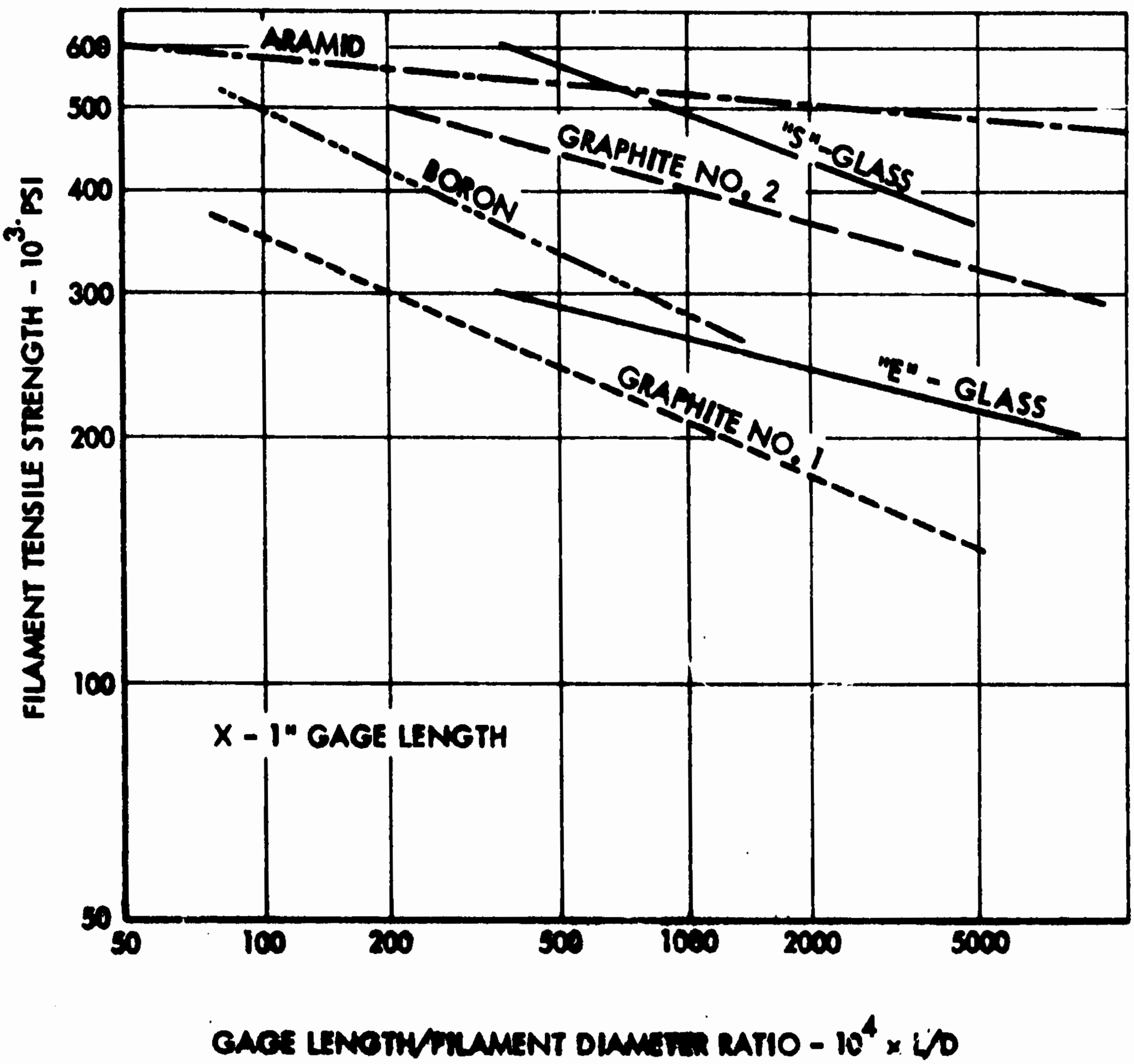


Figure 32. Variation in Tensile Strengths of Various Fibers

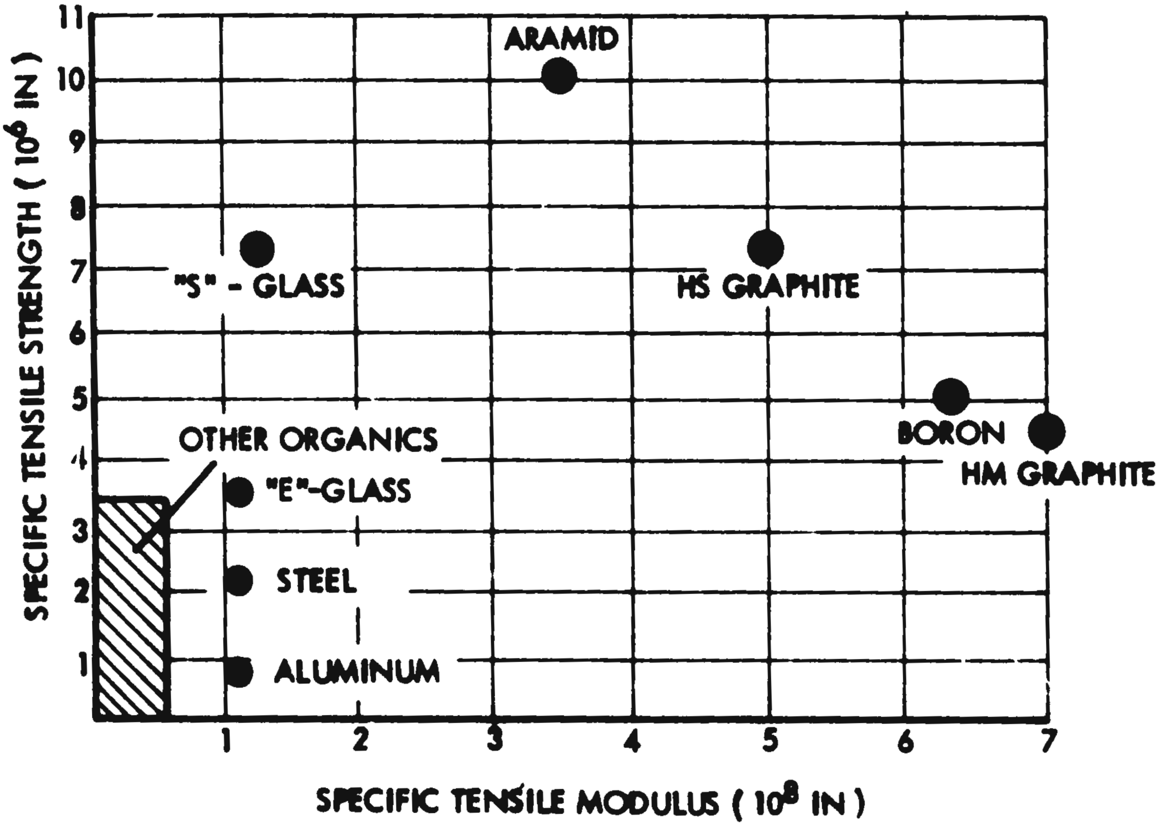
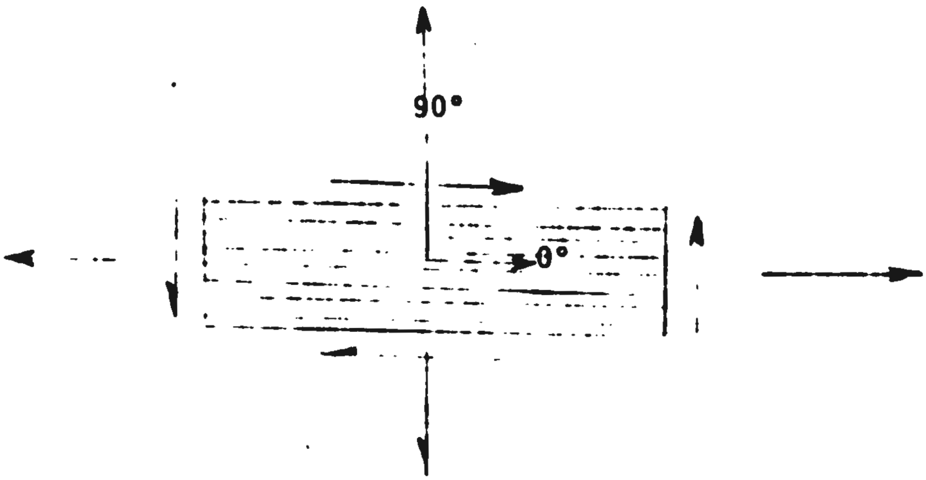


Figure 33. Aramid (Kevlar®) 49 Fibers
(Specific Tensile Strength vs Specified Tensile Modulus)

TABLE 17. UNIDIRECTIONAL COMPOSITE LAMINATE PROPERTIES



	S-GLASS	ARAMID KEVLAR® 49	HS GRAPHITE
Density , lb/ in^3	0.075	0.050	0.055
Tensile Strength 0° (10^3 psi)	160	200	180
Compressive Strength 0° (10^3 psi)	85	10	160
Tensile Strength 90° (10^3 psi)	5.0	4.0	6.0
Compressive Strength 90° (10^3psi)	20	20	20
In-Plane Shear Strength (10^3 psi)	9	6.4	9.0
Interlaminar Shear Strength (10^3psi)	12	14	14
Poisson's Ratio	0.30	0.34	0.25
Tens & Comp Modulus 0° 10^6psi	5.7	12	19
Tens&Comp Modulus 90° 10^6psi	1.8	0.8	0.9
In-Plane Shear Modulus 10^6psi	0.5	0.3	0.7

composite strength. Glass composite technology to remedy such problems is well established. Filament-winding equipment is readily available and very large structures can now be built in glass/polymer composites. Glass filaments are wetted easily by most polymers and glass exhibits very good compatibility with almost all polymer systems currently in use. Present glass strengths still are capable of being improved significantly with only nominal cost increases when compared to other advanced composite reinforcement costs. The flexural modulus of present glass filaments and fibers is significantly lower than other materials, such as graphite and boron. As a measure of comparison, the tensile strengths of glass/resin materials, unreinforced plastics and commonly used metals are shown in Figure 34. In addition, a comparison of principal mechanical properties for different glass/resin material systems is shown in Figure 35.

5.7.5 Composites-Processing

Composite processing is difficult to relate to one simple method of fabrication. The term "composite" implies the mixture or joining of different physical shapes such as flakes, sheets, fibers, fillers, "B" stage, etc. The processing techniques, with applications to shelters, used to form composite materials can be listed as follows:

1. Lamination
2. Impregnation by sprayup of fibers, fabric, or mat
3. Contact lay-up molding
4. Molded laminates (see subsection 5.7.6)
5. Bag molding
6. Wet lay-up, by hand or with automatic tape and fabric-laying machines
7. Vacuum-injection process
8. Cellular laminates
9. Preform molding
10. Filament or tape winding.

In the fabrication of composites consideration must be given to processing of the reinforcing member (fabric) of the material system.

One manufacturing technique that will enhance the availability of promising materials for future use is the three-dimensional weaving process that can orient filaments in three directions. The weaving in the third direction provides isotropic properties. A variety of combinations of woven structures will be possible with the fibers for the 1980's.

This relatively simple process will provide the means of incorporating various fibers into woven panels or socks that can be impregnated with the projected or modified present resin systems. The resultant matrix can be formulated from the basic fiber to the resin material to meet the shelter needs of the future.

The use of thermal expansion rubber tooling can cut the cost of forming laminate composites by increasing processing speed and eliminating the need for expensive autoclaves. Silicone rubbers, tailored to provide a controlled

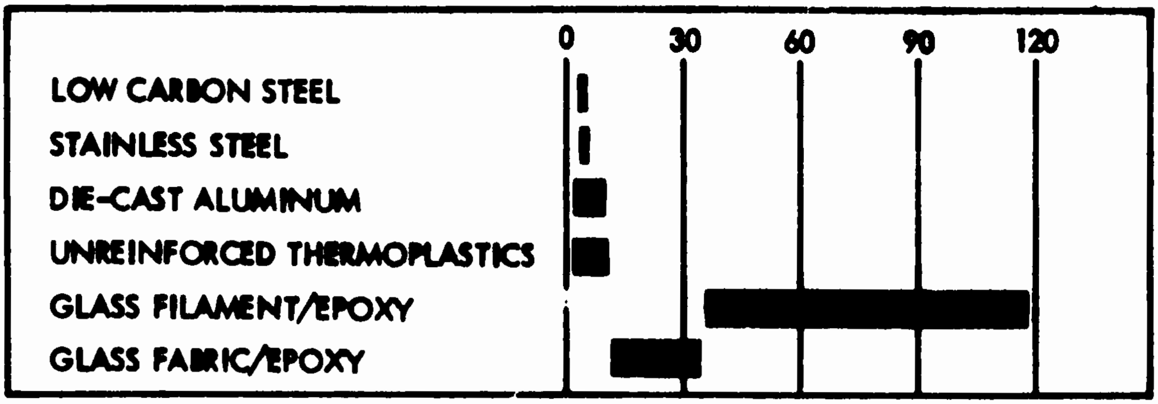


Figure 34. Strength to Weight Comparison Tensile Strength, 10^3 Inches

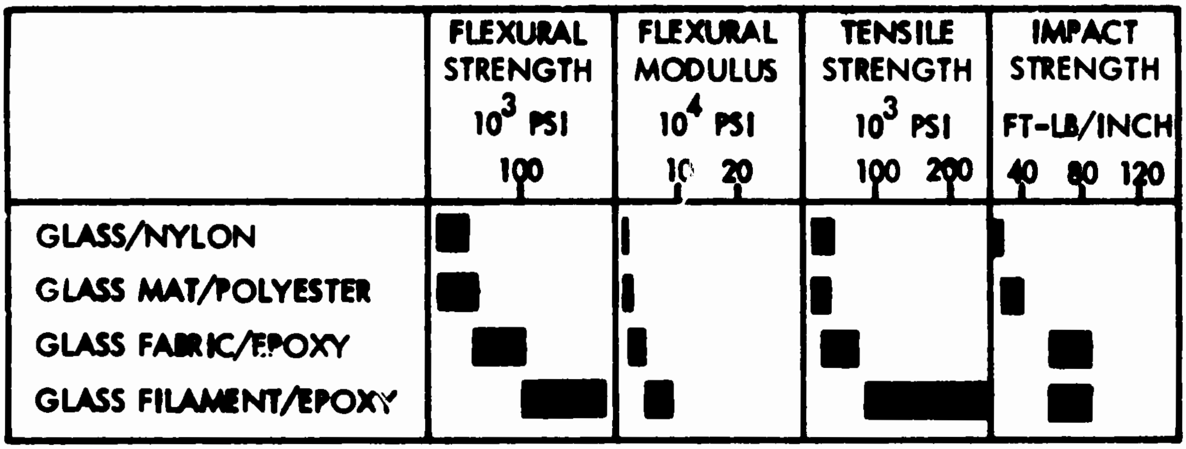


Figure 35. General Properties Comparison for Glass Composites

expansion upon heating, are used in place of conventional female dies. Expansion upon heating forms the reinforced laminates over a male die at high pressures.

An AFML sponsored program uses pressures on the order of 500 psi to form boron/epoxy and graphite/epoxy laminates. NASA (Langley) uses pressures of 600-1000 psi to form graphite polyimide laminates. NASA is also evaluating the hot forming characteristics of linear polyimide laminates formed to shape with integral stiffeners at elevated temperatures and moderate pressures with simultaneous post curing. This type of thermo-forming eliminates the problem of adhesive bonding detail parts to form integral structures and may prove to be an efficient means of processing polyimide composites.

5.7.6 Molding

Molding is usually defined as "the process of forming in or into a particular shape." This definition is a very broad one, and the term may be extended to include extrusion, forming, impregnating, expanding, casting and spinning all of which involve a shaping operation of some kind. Most of the materials presented as material systems to be considered for shelters can be processed from a plastic material by application of one of the following molding techniques:

1. Cold compression molding
2. Hot compression molding
3. Transfer compression molding
4. Injection compression molding
5. Jet compression molding
6. Pultrusion

5.7.7 Foaming

An example of new processes for foamed materials that could be employed for shelter systems is presented in the following discussion. This discussion is presented as an indication of industry's steps toward improving an existing technique so as to enhance material properties.

2.7.7.1 Union Carbide Corp. Process

U. S. Patents Nos. 3, 268,636 and 3,436,466. These processes consist of (1) melting a mixture of a blowing agent and a thermo-plastic material in an extruder at a temperature above the foaming temperature of the blowing agent and at a pressure above its foaming pressure; (2) extruding the molten mixture into an accumulator while maintaining it in the molten state at a pressure above its foaming pressure; and (3) extruding the molten mixture from the accumulator into the mold cavity where the pressure differential between the accumulator and the mold causes the mixture to expand in the mold cavity.

The UCC method is a low pressure molding technique which allows the use of inexpensive molds.

Parts weighing over 100 lbs have been molded by this method. The parts typically have a swirl pattern embossed on their surfaces. Union Carbide reports that it recently has developed a modification of its method whereby smooth, high-gloss moldings can be made.

5.7.7.2 The USBM Process

This process uses an injection molding machine equipped with special types of molds. Resin, containing blowing agent or mixed with a blowing agent, is melted and injected into a closed mold at a controlled rate under high pressure (over 3000 psi) to prevent foaming. When the mold cavity is completely filled with melt, the nozzle on the plasticator closes and the mold cavity is expanded mechanically permitting the melt to foam and form the part having a solid outer skin and foamed core. Tooling costs for this process are relatively high. Parts produced, however, have smoother surfaces than low pressure foamed parts.

5.7.7.3 The ICI Process

U. S. Patent 3,599,290. This process permits the injection molding of foamed parts having smooth, swirl-free outer skins of one material and an inner core of another plastic. In the method, commonly called sandwich molding, an injection molding machine with two injection units is used. Resin from one plasticator is partially injected into the mold cavity and then resin containing the blowing agent is injected from the second plasticator. This forces the first resin to the edges of the mold cavity. The core material expands when the mold is partially opened to lower mold pressure. Parts as large as 20 lbs have been experimentally produced in Europe. Parts now being developed for automobiles and appliances consist of a Noryl Phenylene oxide outer skin and polystyrene foam core. Tooling costs are relatively high.

5.7.7.4 The short-shot method

This method, in which a plastic melt containing blowing agent is injected into a mold cavity but does not quite fill the cavity, thus permitting the material to expand, is probably the most widely used foam molding method in the U.S. Generally, resin and blowing agent are tumble blended, fed into the hopper of the injection molding machine, and then the material is molded in the standard injection molding procedure. In the short-shot technique, molding pressures are low and low-cost tooling can be used. Very large parts can be made by this method. The injection machine has a fixed screw unit which feeds the accumulator from which the material is injected into molds.

5.7.7.5 The Marbon foam casting process

This process basically is a foam-in-place method. Resin, at present only ABS is being used, is poured into a mold cavity to fill it. The mold is closed and heated for a set time to expand and fuse the resin. Compression molding presses and molds have been used to produce parts by this method. Rotational molding equipment also has been used to produce solid foamed parts. Tooling costs are low. Parts produced by the method do not have solid skins as do the other types of structural foam moldings.

5.7.7.6 Structural urethane foam molding processes

These processes, such as Rubicast, Isoderm, Duromer, Cincinnati Milacron, are low pressure methods in which premixed liquid urethane ingredients are metered into a mold, which is then closed and heated. The liquid mixture expands to fill the mold cavity, forming a solid integral skin with a cellular core. Tooling costs for this process are low. Large parts can be made. Equipment for this process ranges from simple, manual, single mold operations to highly automated, multiple tooling (30 molds) operations.

5.7.8 Curing

A key step in processing of resins and composites is the curing method used. Traditionally, the fiber or filler in a composite is preimpregnated with resin or the resin is sprayed or rolled on the fiber, fabric, or mat, and heat and pressure are applied to cure the part, with the pressure used to hold or form the desired part shape, and only secondarily to effect cure.

Successful AFML and commercial programs have been conducted which decrease or eliminate the high cure temperature and pressure requirements. Notable among these methods are:

1. UV cure--correct timing and intensity of ultraviolet light application to polymer-based resins will rapidly and economically cure composites without the need for high temperatures or pressures.
2. Resistance cure--aramid and graphite composites can be low-pressure cured by resistance heating.
3. Microwave cure--microwave energy applied to composite will effect a rapid, low-temperature, low-pressure cure.

5.8 GENERAL DISCUSSION OF GENERIC FAMILIES OF MATERIALS

The following is a general discussion of the relative merits of generic classes of materials. This data, as with the previously presented data, was developed from a variety of sources, including the data noted in the References and Bibliography section that concludes this report.

5.8.1 Comparative Performance

Initially a listing of all possible materials for shelter construction based on existing shelters and existing material properties was made. This long list was narrowed down by viewing all possible materials in light of some required shelter characteristics, such as strength, thermal insulation, electrical conductivity and light weight.

Tables 18 and 29 rank these materials relative to these characteristics. A study based on materials which are now under development and which can significantly improve on the properties of materials listed was then undertaken. This study led to the selection of the materials listed previously in this section.

Following the Tables, general technical and economic characteristics of the various classes of materials are discussed.

Table 18 presents the low temperature properties of a number of elastomers and it is evident that several of these materials can be eliminated early in the material analysis. The relative rating of various materials are shown in the following tables for other properties:

Table 19. Maximum Service Temperature Range
Table 20. Dielectric Strengths
Table 21. Coefficient of Thermal Expansion
Table 22. Thermal Conductivity
Table 23. Water Absorption
Table 24. Specific Heat
Table 25. Chemical Resistances
Table 26. Specific Strength of Plastics
Table 27. Tensile Strength
Table 28. Modulus of Elasticity in Tension
Table 29. Flexural Strength.

The data of these tables indicates that the ultimate selection of a material system will be a compromise between the desirable and the obtainable properties. For example, the relative ranking of silicone is:

- Maximum service temperature 4
- Dielectric strength 42
- Coefficient Thermal expansion 12
- Thermal conductivity 21
- Water absorption 6
- Specific strength 45
- Tensile strength (asbestos filler) 28

5.8.2 Thermoplastic Resins Candidates

5.8.2.1 ABS (Acrylonitrile-Butadiene-Styrene)

Three basic monomers (acrylonitrile, butadiene, and styrene) go into the creation of the ABS thermoplastic resins. Fabricated shapes from these resins exhibit good dimensional stability, wear resistance, low moisture

TABLE 18. LOW-TEMPERATURE PROPERTIES OF ELASTOMERS

Elastomer	Brittleness Temperature (°F)	Temperature Retraction (°F)		Temperature Where Young's Modulus Is 10,000 psi (°F)	Gehman Low-Temperature Values (°F)*		
		TR 10	TR 70		T_2	T_5	T_{100}
Polyacrylics	5 to -15	...	...	5 to -15	...	...	...
Butyl	-60 to -75	-70	-22	-60 to -75	...	...	...
Neoprenes	-30 to -60	-40	-48	-35 to -65	...	...	...
Nitriles	-60 to -75	...	...	...	10	-8	-35
EPDMs	-90 to -100	-46	-15	-60 to -80	15	-30	-56
Polysulfide	-50 to -65	...	...	-65	...	...	...
Natural Rubber	-70	-70	27	-65 to -75	...	...	...
SBRs	-65 to -80	-42	-10	-45 to -65	...	...	...
Silicone (low-temp stock)	-175	...	...	-150	...	...	...
Flouroelastomers	-40 to -50	5	30	-10 to -20	15	5	-9
Flourosilicones	-90	...	...	-80	...	...	...
Epichlorohydrins	-40 to -90	-80	-65	-40 to -75	-40	-60	-80
Urethanes	-30 to -80	...	...	-30 to -40	-18	-33	-88
Chlorosulfonated polyethylene	-40 to -60	...	...	...	...	...	...
Cis-polybutadienes	-135 to -160	...	...	-120 to -130	-36	-80	-132

*Test indicating increase in stiffness as temperature drops. Values for T_2, T_5, and T_{100} are the temperatures at which the relative modulus (or stiffness) of the elastomers is 2, 5, and 100 times the modulus at room (23°C) temperature.

TABLE 19. MAXIMUM SERVICE TEMPERATURE[a] RANGE

Rating	Type	Temperature °F High	Low
1	Silicones (molded)	700	600
2	Silicone Foams	650	500
3	TFE Film	585	566
4	Silicone Rubber	550	-
5	Plastic Laminates, Low Pressure	500	250
6	TFE Fluorocarbons	500	-
7	Polyester Film	490	-
8	Diallyl Phthalate	450	300
9	Fluorinated Acrylic Rubber	450	-
10	Phenolics, Shock and Heat Resistant	450	250
11	Viton Rubber	450	-
12	Cellulosic Films	400	140
13	Epoxies (cast), Heat Resistant	400	-
14	FEP Fluorocarbons	400	-
15	Melamines, Glass-Filled	400	300
16	Nylon, Glass-Filled	400	300
17	Phenolics (molded), Shock and Heat Resistant	400	350
18	Plastic Laminates, Electrical	400	160
19	Urethane Foamed-in-Place, Rigid	400	-
20	Melamines Cellulose or Mineral-Filled	395	205
21	CFE Fluorocarbons	380	-
22	Nylon 6 Film	380	-
23	Alkyds, High Strength	350	-
24	Phenolics (molded), General Purpose	350	300
25	Prefoamed Cellulose Acetate, Rigid	350	200
26	Alkyds, General Purpose	345	295
27	Allyls (cast)	300	-
28	Butyl Rubber	300	-
29	Diallyl Phthalate, Orlon-Filled	300	-
30	Nylon 66 and 610	300	225
31	Phenolic Foamed-in-Place, Rigid	300	-
32	Polypropylene Film	300	-
33	Rubber Phenolics	300	212
34	Plastic Laminates, General Purpose	295	245
35	Polyester (cast), Rigid	295	245
36	Polyvinylidene Chloride	290	-
37	Polycarbonate	275	250
38	Melamines, Fabric-Filled	250	-
39	Melamines, Shock Resistant	250	-
40	Nitrile Rubber	250	-
41	Nylon 6 and 11	250	200
42	Polyethylene Film	250	200
43	Polysulfide Rubber	250	-
44	Neoprene Rubber	240	-
45	Urethane Rubber	250	-
46	Polyallomer	230	180
47	Polyvinyl Chloride	220	140
48	Acetal Copolymer	220	-
49	Vinylidene Chloride	212	170
50	Melamines, General Purpose	210	-
51	Butadiene-Acrylonitrile Foams	210	-
52	Rubber Hydrochloride Film	205	-
53	Acrylics	200	140
54	Polystyrenes, Glass-Filled	200	190
55	Pre-Nitrile Rubber Blend Film	200	-
56	Urethane Foams, Flexible	200	-
57	Modified Polystyrenes	190	120
58	Acetal	185	-
59	Polystyrene Foamed-in-Place, Rigid	185	-
60	Natural Rubber	180	-
61	Neoprene Foams	180	-
62	Polystyrenes, General Purpose	180	140
63	Polyvinyl Chloride Film	180	150
64	Styrene-Butadiene Rubber	180	-
65	Epoxies (cast), General Purpose	175	-
66	Phenoxy	175	155
67	Prefoamed Polystyrene, Rigid	175	155
68	Polyvinyl Formal	165	130
69	Butadiene-Styrene Foams	160	-
70	Natural Rubber Foams	160	-
71	Cellulose Nitrate	140	120
72	Epoxies (cast), Resilient	122	-
73	Polyvinyl Butyral	115	-

Note:

a. Values represent high and low side of a range of typical values. Conversion Factor: to obtain °C, subtract 32 and multiply by 5/9.

TABLE 20. DIELECTRIC STRENGTH[a]

Rating	Type	Volts per mil High	Volts per mil Low
1	Polymethylstyrene	1950	
2	Polyvinyl Chloride	1400	24
3	Acetal Copolymer	1200	-
4	Polyvinyl Formal	1000	860
5	Plastic Laminates, High Pressure	1000	70
6	Polypropylene	800	520
7	Plastic Laminates, Low Pressure	800	100
8	Modified Polystyrenes	650	-
9	Polyallomer	650	-
10	Cellulose Acetate	600	250
11	Cellulose Nitrate	600	300
12	CFE Fluorocarbons	600	530
13	Hard Rubber	600	344
14	Polyesters (cast), Rigid	570	340
15	Epoxies, (cast)	550	350
16	Acrylics	530	400
17	Polystyrenes, General Purpose	7500	-
18	Acetal	500	-
19	Ethyl Cellulose	500	350
20	Nylon, Glass-Filled	500	400
21	Nylons 6 and 11	500	420
22	Polyesters (cast), Allyl Type	500	400
23	TFE Fluorocarbons	500	400
24	Polyethylenes	480	-
25	Polycarbonates, Filled	475	-
26	Nylons 66 and 610	470	385
27	Epoxies (molded)	468	334
28	Cellulose Propionate	450	300
29	Diallyl Phthalate	450	275
30	Phenolics (cast), General Purpose	450	300
31	Melamines, Electrical	430	350
32	Phenolics (molded), General Purpose	425	200
33	Polystyrenes, Glass-Filled	425	340
34	ABS Resins, High Impact	416	350
35	Cellulose Acetate Butyrate	400	250
36	Chlorinated Polyether	400	-
37	Melamines Cellulose Electrical	400	350
38	Phenolics (cast), Mechanical and Chemical	400	350
39	Polycarbonate	400	-
40	Polyesters (cast), Nonrigid	400	200
41	Polyvinyl Butyral	400	-
42	Silicones (molded)	400	250
43	Ureas	400	300
44	Rubber Phenolics	375	250
45	Melamines, Shock Resistant	370	130
46	Phenolids (molded), Very High Shock	370	200
47	Alkyds	350	300
48	Phenolics, Heat Resistant	350	100
49	Melamines, General Purpose	330	310
50	ABS Resins, Extra High Impact	312	-
51	Phenolics (cast), General Purpose, Transparent	250	75
52	Polyethylene Foam, Flexible	220	-

Note:
a. Values represent high and low sides of a range of typical values. Conversion Factor: to obtain V/cm, multiply by 393.7.

TABLE 21. COEFFICIENT OF THERMAL EXPANSION[a]

Rating	Type	10^{-6}in/in/°F High	Low
1	Plastic Laminates, Low Pressure	14	10
2	Epoxies (molded)	14	-
3	Ureas	15	12
4	Plastic Laminates, High Pressure	17	5.5
5	Nylon, Glass-Filled	17	12.5
6	Prefoamed Epoxy, Rigid	22	16
7	Polystyrene, Glass-Filled	24	22
8	Prefoamed Polystyrene, Rigid	25	-
9	Prefoamed Cellulose Acetate, Rigid	25	20
10	Phenolics (molded)	25	8.3
11	Melamines and Alkyds	31.7	3.2
12	Silicones (molded)	32.2	4.5
13	Polyvinyl Chloride	33	28
14	Phenoxy	35	30
15	Diallyl Phthalate	35	15
16	Polycarbonate	37	10
17	CFE Fluorocarbons	38.8	-
18	Polyvinyl Formal	42.7	35.5
19	Polystyrenes, General Purpose	44	43
20	Acetal and Chlorinated Polyether	45	44
21	Urethane Foams	50	14
22	Polyallomer	50	-
23	Acrylics and Epoxies (cast)	50	30
24	TFE Fluorocarbons	55	-
25	Nylon 66 and 610	55	-
26	Polyester (cast)	56	28
27	Phenolics (cast)	66	33
28	Cellulose Nitrate	66	44
29	Polyvinyl Alcohol	66.5	38.8
30	Nylons 6 and 11	71	46
31	ABS resins and Modified Polystyrenes	73	32
32	Vinylidene Chloride	87.8	-
33	Cellulose Acetate and Propionate	90	44
34	Polyethylenes, Low Density	110	89
35	Ethyl Cellulose	110	55
36	Polyvinyl Butyral	127	44
37	Polyethylenes, Medium and High Density	167	83
38	Polypropylene	170	-
39	Butyl Rubber	320	-
40	Neoprene Rubber	340	-
41	Natural, Styrene-Butadiene Rubber	370	-
42	Nitrile Rubber	390	-
43	Silicone Rubber	670	-

Notes:

a. Values represent high and low side of a range of typical values. Value for plastics materials are for a range of temperatures between -22°F and 86°F (ASTM D-696). Conversion Factor: to obtain in./in./°C, multiply by 1.80.

TABLE 22. THERMAL CONDUCTIVITY[a]

Rating	Type	BTU/hr/sq.ft./°F/ft		Rating	Type	BTU/hr/sq.ft./°F/ft	
		High	Low			High	Low
1	Epoxies (cast)	0.80	0.10	23	Neoprene Rubber	0.11	-
2	Alkyds	0.60	0.20	24	Polycarbonate	0.11	0.05
3	Polyvinyl Alcohol	0.46	-	25	Polyvinyl, Chloride	0.10	0.07
4	Melamines	0.41	0.17	26	Silicones (molded)	0.097	0.089
5	Phenolics (molded)	0.39	0.10	27	Polyvinyl Formal	0.09	-
6	Plastic Laminates, High Pressure	0.29	0.17	28	Natural Rubber	0.08	-
				29	Polystyrenes, General Purpose	0.08	0.05
7	Ureas	0.24	0.17				
8	Cellulose Acetate and Propionate	0.17	0.10	30	Modified Polystyrenes	0.07	0.02
				31	Butyl Rubber	0.05	-
9	Polyethylenes	0.19	-	32	Vinylidene Chloride	0.05	-
10	Ethyl Cellulose	0.17	0.09	33	Urethane Foamed-in-Place, Rigid	0.03	0.01
11	CFE Fluorocarbons	0.145	-				
12	Nylons 6, 11, 66 and 610	0.14	0.10	34	Neoprene Foams	0.029	0.021
13	Styrene-Butadiene and Nitrile Rubber	0.14	-	35	Prefoamed Cellulose Acetate, Rigid	0.027	0.025
14	TFE Fluorocarbons	0.14	-	36	Butadiene-Acrylonitrile Foams	0.025	0.021
15	Acetal	0.13	-				
16	Cellulose Nitrate	0.13	-	37	Natural Rubber Foams	0.025	0.021
17	ABS Resins	0.12	0.08	38	Silicone Foams, Rigid	0.025	-
18	Acrylics	0.12	0.10	39	Phenolic Foamed-in-Place Rigid	0.02	-
19	Nylon, Glass-Filled	0.12	-				
20	Polyester (cast)	0.12	0.10	40	Polystyrene Foamed-in-Place, Rigid	0.02	-
21	Silicone Rubber	0.12	0.11				
22	Polypropylene	0.11	0.10	41	Prefoamed Epoxy, Polystyrene, Rigid	0.02	-
				42	Butadiene-Styrene Foams	0.018	-

Note:
a. Values represent high and low sides of a range of typical values at room temperature. Conversion Factor: to obtain cal/sec/sq cm/°C/cm, multiply by 0.004.

TABLE 23. WATER ABSORPTION[a]

Rating	Type	Percent
1	Polychlorotribluoroethylene	0.00
2	Polypropylene	0.01
3	Polyethylene	0.015
4	Polystyrene	0.04
5	Epoxy	0.10
6	Silicone	0.15
7	Polycarbonate	0.30
8	Alpha-Melamine	0.35
9	Phenolic	0.60
10	Urea	0.65
11	Nylon	1.50
12	Cellulose Acetate	3.80

TABLE 24. SPECIFIC HEAT[a]

Rating	Type	Btu/lb/°F or Cal/gm/°C High	Low
1	Silicones	0.20	-
2	CFE Fluorocarbons	0.22	-
3	Vinyls	0.23	-
4	TFE Fluorocarbons	0.25	-
5	Prefoamed Polystyrene, Rigid	0.27	-
6	Polystyrene, Glass-Filled	0.27	0.24
7	Polycarbonate	0.30	-
8	Polyvinyl Alcohol	0.30	-
9	Vinylidene Chloride	0.32	-
10	Phenolics, Very High Shock	0.32	0.28
11	Rubber Phenolics	0.33	-
12	Phenolics, High Shock	0.35	0.31
13	Nylon, Glass-Filled	0.35	0.30
14	Modified Polystyrene	0.35	0.30
15	Acrylics	0.35	0.34

Rating	Type	Btu/lb/°F or Cal/gm/°C High	Low
16	Acrylics	0.35	0.34
17	ABS Resins	0.38	0.35
18	Urea	0.40	-
19	Polyvinyl Butyral	0.40	-
20	Phenolics, General Purpose	0.40	0.36
21	Cellulose Propionate	0.40	0.30
22	Cellulose Acetate Butyrate	0.40	0.30
23	Cellulose Acetate	0.42	0.30
24	Polypropylene	0.46	-
25	Nylon 66 and 610	0.50	0.30
26	Polyethylenes	0.55	0.46
27	Polyester, Rigid	0.56	0.30
28	Allyl (cast)	0.56	0.26
29	Ethyl Cellulose	0.58	-
30	Nylon 6 and 11	0.60	0.40

Note:

a. Values represent high and low sides of a range of typical values.

TABLE 25. COMPARATIVE CHEMICAL RESISTANCE[a]

Rating	Type
1	Polytetrafluoroethylene (TFE)
2	Fluorethylene Propylene (FEP)
3	Polytrifluorochloroethylene (TFCE)
4	Chlorinated Polyether
5	Polypropylene
6	Polyethylene
7	Polycarbonate

Rating	Type
8	Phenolics
9	Nylon
10	Polyvinylidene Chloride
11	Polyvinyl Chloride
12	Polyester
13	Melamine

Note:

a. This table attempts to rate various plastics according to their overall resistance to chemicals. If the ratings were resistant to acids or to alkalies separately, the results would be different. Nylon molding powder, for instance, is not affected by alkalies.

TABLE 26. SPECIFIC STRENGTH OF PLASTICS[a]

Rating	Type	Strength to Weight Ratio (1000 in.)
1	Reinforced Plastics, Filament-Wound	4310
2	Reinforced Plastics, Epoxy	1635
3	Reinforced Plastics, Phenolic	1018
4	Reinforced Plastics, Polyester	1000
5	Reinforced Plastics, Silicone	752
6	Plastic Laminate, High Pressure	638
7	Nylon, Glass-Filled	574
8	Epoxies (cast)	368
9	Nylon 66	360
10	Polystyrene, Glass-Filled	335
11	Modified Polystyrenes	333
12	Nylon 6	323
13	Wethane Foams	300
14	Epoxies (molded)	296
15	Acrylics (molded, extruded)	292
16	Polycarbonate	284
17	Acrylics (cast)	278
18	ABS Resins	266
19	Nylon 610	258
20	Polyesters (cast)	250
21	Nylon 11	250
22	Polyvinyl Butyral	250
23	Polystyrene, General Purpose	250
24	Acetal	227

Rating	Type	Strength to Weight Ratio (1000 in.)
25	Phenolics (cast)	225
26	Hard Rubber	224
27	Ureas	217
28	Melamines, General Purpose	217
29	Cellulose Acetate	213
30	Polyvinyl Chloride	209
31	Acrylics, High Impact	209
32	Ethyl Cellulose	206
33	Cellulose Propionate	203
34	Cellulose Nitrate	190
35	Polypropylene	185
36	Cellulose Acetate Butyrate	184
37	Phenolics, (molded)	179
38	Alkyds, Impact	159
39	Polyethylene, High Density	152
40	Diallyl Phthalate	146
41	Chlorinated Polyether	140
42	Vinylidene Chloride	133
43	Polyvinyl Alcohol	128
44	Polyethylene Low Density	89
45	Silicones (molded)	89
46	CFE Fluorocarbons	88
47	Polyethylene Medium Density	83
48	Alkyds, General Purpose	
49	TFE Fluorocarbons	51

Note:

a. Specific strengths (strength-weight ratios) are obtained by dividing tensile strengths (psi) of plastics by density (lb/cu. in.).

TABLE 27. TENSILE STRENGTH[a]

Rating	Type	Tensile Strength (10^3 psi) High	Low
1	Glass Fibers	220	200
2	Cellulosic Fibers	155	20
3	Nylon Fibers	128	55
4	Polyester Fibers,	126	67
5	Cotton Fibers	109	44
6	Asbestos Fibers	100	80
7	Polyethylene Fibers	90	11
8	Plastic Laminates, Low Pressure	85	8
9	Acrylic Fibers	57	26
10	Fluorocarbon Fibers	47	-
11	Vinyl Fibers	45	12
12	Vinylidene Chloride	40	4
13	Plastic Laminates, High Pressure	37	7
14	Nylon, Glass-Filled	31	19
15	Polyester, Glass Reinforced	30	-
16	Silicone, Asbestos Filled	28	-
17	Polyester Film	28	17
18	Cellophane	19	7
19	Epoxy, Glass Reinforced	17	-
20	Nylon 6, Film	17	13.8
21	Polystyrene, Glass-Filled	17	11
22	Epoxies (molded)	16	5
23	Polyvinylidene Chloride Film	15	7
24	Nylon 66 and 610	12.6	7.1
25	Epoxies (cast)	12	0.1
26	Nylon 6 and 11	12	8.5
27	Polystyrene Film	12	7
28	Modified Polystyrenes	11	3
29	Polyvinyl Formal	11	9
30	Acrylics (molded, extruded)	10.5	5.5
31	Acetal	10	-
32	Alkyds, Impact	10	6
33	Ethyl Cellulose Film	10	6
34	Melamines, Phenolics (molded)	10	3.5
35	Polyesters (cast)	10	0.9
36	Polypropylene Film	10	5
37	Polyvinyl Alcohol Film	10	6
38	Ureas	10	5
39	Polycarbonates	9.5	9
40	Phenoxy	9.5	9
41	Hard Rubber	9.3	2
42	Phenolics (cast)	9	2.5
43	Polyvinyl Chloride	9	1
44	ABS Resins	8.5	3
45	Cellulose Acetate	8.5	1.9
46	Polyvinyl Butyral	8.5	4
47	Polyvinyl Chloride Film, Rigid	8.5	6.5
48	Acrylics (cast), General Purpose	8	6
49	Cellulose Nitrate	8	7
50	Polyethylene Film	8	1.6
51	Polystyrenes, General Purpose	8	5
52	Cellulose Propionate	7.5	1.5
53	Acrylics, High Impact	7.3	5.5
54	Diallyl Phthalate	7	4
55	Ethyl Cellulose	7	3
56	Cellulose Acetate Butyrate	6.8	1.9
57	CFE Film	6.6	6.3
58	Chlorinated Polyether	6	-
59	Rubber Hydrochloride	6	[illegible]
60	Urethane Rubber (gum)	75	-
61	CFE Fluorocarbons	5.7	4.6
62	Polypropylene	5	-
63	Polyvinyl Alcohol	5	1
64	Polyvinyl Chloride Film, Nonrigid	5	1
65	Silicones (molded)	5	4
66	Natural Rubber (black)	4.5	3.5
67	Nitrile Rubber (black)	4.5	3
68	Polyethylene, High Density	4.4	2.9
69	Polyallomer	4.2	3.5
70	Alkyds, General Purpose and Electrical	4	3
71	Neoprene Rubber (black)	4	3
72	PVC - Nitrile Rubber Blend Film	4	1.5
73	Styrene-Butadiene Rubber (black)	3.5	2.5
74	TFE Fluorocarbons	3.5	2.5
75	Butyl Rubber (black)	3	2.5
76	TFE Film	3	2
77	Polyethylene, Medium Density	2.4	2
78	Viton Rubber (gum)	2	-
79	Fluorinated Acrylic Rubber (gum)	1.2	-
80	Urethane Foamed-in-Place, Rigid	1.2	0.01
90	Polysulfide Rubber (gum)	1	-
91	Silicone Rubber (gum)	1	0.6
92	Polyethylene, Low Density	0.9	0.5
93	Polyethylene Foam, Flexible	0.67	-
94	Prefoamed Epoxy, Rigid	0.65	0.05
95	Vinyl Foams, Flexible	0.2	0.01
96	Prefoamed Polystyrene, Rigid	0.19	0.03
97	Prefoamed Cellulose Acetate, Rigid	0.18	0.11
98	Polystyrene Foamed-in-Place, Rigid	0.13	0.03
99	Neoprene Foams	0.01	0.02
100	Butadiene-Styrene Foams	0.08	-
101	Phenolic Foamed-in-Place, Rigid	0.075	0.004
102	Butadiene-Acrylonitrile Foams	0.04	-
103	Natural Rubber Foam	0.02	0.01

Note:

a. Values represent high and low side of a range of typical values. Conversion Factor: to obtain °C, subtract 32 and multiply by 5/9.

b. Values represent high and low sides of a range of typical values at room temperature. Strength varies greatly with different fillers and reinforcements. Nylon, for instance, varies from 7,000 to 30,000 psi, depending on type and filler.

TABLE 28. MODULUS OF ELASTICITY IN TENSION[a]

Rating	Type	10^5 psi High	10^5 psi Low
1	Phenolic Electrical	50	30
2	Phenolics, Shock and Heat Resistant	33	8
3	Epoxy, Glass-Fiber Filled	30	-
4	Melamines, Filled	19.5	9
5	Ureas	16	13
6	Phenolics, General Purpose	13	7
7	Polystyrenes, Glass-Filled	13	11
8	Diallyl Phthalate	12	6
9	Rubber Phenolics	9	1
10	Nylon, Glass-Filled	8.6	1.2
11	Polyvinyl Formal	7	5
12	Modified Polystyrenes	6	2.5
13	Acrylics, General Purpose	5	3.5
14	Phenolics (cast), Mechanical and Chemical	5	4
15	Polystyrenes, General Purpose	5	4
16	Nylon 66 and 610	4.1	1.6
17	Phenoxy	4	3.8
18	ABS Resins	4	1.0
19	Acetal Copolymer	4	-
20	Polyvinyl Butyral	4	3.5
21	Nylon 6 and 11	3.6	1.5
22	Polycarbonates	3.5	1.3
23	Ethyl Cellulose	3.5	0.5
24	Acrylics, High Impact	3	2.2
25	Allyls (cast)	3	2
26	CFE Fluorocarbons	3	1.9
27	Phenolics (cast), Transparent	3	1
28	Polypropylene	2.9	1.2
29	Cellulose Nitrate	2.2	1.9
30	Vinylidene Chloride	2	0.7
31	Polyallomer	1.9	0.8
32	TFE Fluorocarbons	0.65	0.38
33	Polyethylene, Low Density	0.27	0.2
34	Polyvinyl Chloride, Nonrigid	0.03	0.004

Note:
a. Values represent high and low sides of a range of typical values at room temperature.

TABLE 29. FLEXURAL STRENGTH

Rating	Type	PSI x 10^3
1	Laminated Phenolic	27
2	Epoxy	24
3	Nylon	17
4	Phenolic	15
5	Melamine	14
6	Polycarbonate	12
7	Polystyrene	11.5
8	Vinyl Rigid	11
9	Polyester	9
10	Polyethylene, Medium Density	6
11	Chlorinated Polyether	5

absorption and negligible creep at room temperature and low sustained loads. Although the present resin system supports combustion and is attached by solvents, the system has potential. The large number of possible modifications of this resin system give promise for its future application to shelter concepts as major structural elements.

5.8.2.2 Acetal

At present there are two types of acetals: a homopolymer and a copolymer. In general, the copolymer has better stability and resistance to heat aging, while the homopolymer offers slightly better "as molded" mechanical properties. The copolymer resin has been selected for consideration as a possible material for shelter fabrication because of its higher fatigue endurance limit, dimensional stability, stable physical properties and excellent recovery from loading. The acetal resins have a high potential for modification to improve their molding characteristics and are therefore considered for shelter structural elements.

5.8.2.3 Acrylic

The acrylic resins are based largely upon the homopolymerization of methacrylic or acrylic esters to form the polymer molecule. The acrylics exhibit excellent resistance to weathering, cracking, fungi, water absorption and impact. The fabricated materials are readily bonded and heat sealed, have good electrical insulating properties, but have a tendency to cold flow (creep) under low loads and do have a low softening temperature (160°F).

Future research and development work holds promise in modifying these resins in such a way as to increase their resistance to cold flow, increase their softening temperature, improve their physical and mechanical properties and improve their corrosion resistance.

5.8.2.4 Cellulosics

There are four prominent industrial cellulosics: cellulose acetate, cellulose acetate butyrate, cellulose acetate propionate, and ethyl cellulose. This resin system is capable of being modified to improve its molding characteristics, self-extinguishing performance and to reduce the tendency of plasticizers to migrate to the surface when exposed to elevated temperatures. Their poor resistance to chemical attack will most probably limit their use as shelter elements.

5.8.2.5 Chlorinated Polyethers

The chlorinated polyether resins are corrosion-resistant thermoplastics that have proven exceptionally useful in the design and production of equipment for chemical processing systems. These resins are capable of producing parts which will retain their mechanical properties at temperatures up to 280°F, will have low water absorption rates, are self-extinguishing and have excellent dimensional stability. This resin system holds promise for application to future shelter systems in the area of service shelters such as kitchens, latrines, floor panels, etc.

5.8.2.6 Fluorocarbon

Four classes of fluorocarbon resins (commonly called Teflon®) are commercially available:

1. TFE, polytetrafluoroethylene
2. FEP, a copolymer of polytetrafluoroethylene and hexafluoropropylene
3. CTFE, polychlorotrifluoroethylene, a resin that contains chlorine as well as fluorine
4. Polyvinylidene fluoride.

The fluorocarbon resins (commonly called Teflon®) have excellent resistance to chemical attack; very low coefficient of friction; retain their toughness at cryogenic temperatures; have excellent electrical insulation characteristics; and resist sticking. However, molded parts tend to cold flow under load and are relatively difficult to fabricate. Their application to future shelters appears to be limited to ancillary applications such as wire insulation, etc.

5.8.2.7 Polyamides (Nylons)

Nylon is the common name for polyamides. The nylons are identified by the number of carbon atoms in the parent diamine and dibasic acid. These materials are principally useful when woven into fabrics or cordage. The fabrics can be impregnated with hypalon or neoprene to produce a water and air-tight material. This material has application in "air supported" shelters and when coated with Teflon® can be used as a mold for "foam in place" structures.

Continued research in the amides resin family has produced the "aramid" material (Kevlar®) that is one of the new materials for eventual use during the 1980 period.

5.8.2.8 Polycarbonates

Polycarbonate resins are derived from aromatic and aliphatic dihydroxyl compounds. These thermoplastics have exceptional combinations of properties which make them useful in many applications. While many variations are possible in the final structure, the present commercial product is based on bisphenol A. The polycarbonate resins are readily injection-molded into a variety of shapes. The molded shape can be produced as a solid piece or, by blow molding, a foamed piece having solid skins with a uniform gradation to foam at the center. Future modifications of these resins would make them applicable to shelter concept components such as molded structural/insulating members.

5.8.2.9 Polyethylenes

Polyethylene is made from ethylene gas and is manufactured by both a low- and high-pressure process. In general, polyethylene made by the high-pressure process has a branched structure and high density while that made by the low-pressure process is relatively unbranched and has a lower density. The length of the branches, the amount of branching, and the average length of the polymer chain are controlled by the catalyst, the monomers used, and the temperature and pressure used in the process. The system used to classify polyethylene resins is based on their relative densities. The polyethylene resins are capable of being modified to improve their molding characteristics, including foamability and general mechanical characteristics. Improvements in several physical and foaming characteristics will be required to make this material become a useful insulating semi-structural material for shelters. Ultra-high molecular weight polyethylene moldings exhibit superior toughness and strength; in the 1980's this material with these characteristics, when combined with the material's low density, will find wide application in structural fittings and wear surfaces.

5.8.2.10 Polypropylenes

In making polypropylene, the catalyst and polymerization conditions can be varied to give four main types of polymers: isotactic, syndiotactic, atactic and stereoblock. The isotactic polymer has found the largest commercial use. It is characterized by a regular spatial structure in which the methyl groups of the propylene monomeric units occupy the same relative position in space along the chain which, in the crystallized state, assumes a spiral-like configuration. For most commercial applications, 95 to 98 percent isotactic content in the final polymer is desirable. The principal factors which influence the physical and mechanical properties of polypropylene are: (1) isotactic polymer content, (2) average molecular weight, and (3) distribution of molecular weight. The resins have exceptional resistance to environmental stress cracking, do not absorb moisture, and are highly resistant to chemical attack and staining. They are unaffected by inorganic salts, mineral acids and bases and polar organic solvents. The polypropylene resins produce parts which are tough, resist impact, are dimensionally stable, have a high surface hardness and abrasion resistance. Principal weaknesses of these resin materials are their high creep rate which may tend to limit their usefulness in shelter systems.

5.8.2.11 Polystyrenes

Polystyrene is a water-white thermoplastic material produced from coal-tar and petroleum. Mechanical properties can be altered by adding modifying agents such as: rubber for impact strength, methyl or alpha styrene for heat resistance, methyl methacrylate for light stability, and acrylonitrile for chemical resistance. The high heat materials are produced as copolymers, while the high impact materials are produced by blending. The resins can be dyed an infinite number of colors and can be modified by selected additions, such as rubber, to improve their toughness and rigidity. Future research and development work with this resin system may produce a material with self-extinguishing characteristics and better mechanical properties for eventual use in shelter systems.

5.8.2.12 Vinyls

The vinyls are versatile groups of thermoplastic resins that range in properties from soft flexible sheetings to hard rigid shapes. The term "vinyl" comes from the chemical radical $CH_2{=}CH-$, which has many derivatives. When attached to a chlorine atom, it becomes vinyl chloride $CH_2{=}CH\ Cl$; when attached to an acetate group, it becomes vinyl acetate $CH_2{=}CH\ COCH_3$. Other derivatives are the alcohols, butyrals, formal, and the new heat resistant dichloride (vinylidene dichloride). With these derivatives, a great many polymers can be made, either as homopolymers of themselves, or copolymers in combination with another vinyl derivative or other monomeric material.

The polyvinyl chloride and dichloride resins retain their mechanical properties over a wide temperature range. The dichloride, a high heat resistant material, withstands temperatures about 60°F higher than other vinyls; for example, at 212°F the material retains a strength of 2100 psi.

Rigid vinyls withstand strong acids and alkalies, metallic and ammonia salts, and organic media such as alcohol and aliphatic hydrocarbons. Industrial fumes and salt water do not seriously degrade the property of rigid vinyls. The vinyls are not resistant to organic solvents and will swell when exposed to aromatic hydrocarbons.

The polyvinyl chloride resins show great promise for future shelter applications, particularly in the foamed extruded area. Modifications to existing resins have made it possible to produce rigid foam extrusions with a density one-third that of the solid material. These extrusions can be produced with or without a hard skin and can be sawed, routed, machined, nailed, etc., with greater ease than wood and can be decorated with vinyl film, etc. Proposed applications are: shelving, window frames and door moldings. Because of its versatility and adaptability, these resin systems show a good possibility for use in the 1980's time frame.

5.8.2.13 Polyallomers

These resin systems were introduced in 1962 and are defined as crystalline thermoplastics produced from two or more different monomers. These materials belong to the polyolefin family of plastics which includes polyethylene and polypropylene. These propylene-ethylene polyallomers are currently available in high stiffness, medium-impact and high-impact formulations.

The resin system's low-softening temperatures and low brittleness temperature requires considerable modification to make it practical for use as a shelter material component.

5.8.2.14 Physical and Mechanical Properties

The physical and mechanical properties of thermoplastic resins are shown in Table 30.

5.8.3 Thermosetting Resins Candidates

5.8.3.1 Alkyds

The initial reaction in the formation of alkyd (term derived from alcohol and acid) resins is the condensation of a dibasic acid or anhydride with a polyhydric alcohol, to form a partial condensation polymer. The two most commonly used components are phthalic anhydride and glycerin. Solubility in aromatic or aliphatic solvents is developed by introducing into the resin molecule a monobasic acid, usually a long-chain fatty acid.

The overall physical characteristics of this system indicate that the material can be employed for use in future shelter systems. Specific material properties that will require resin modification prior to use in shelter systems are to improve the impact strength of the material and correcting some difficulties in mass production of molded elements to close tolerances.

5.8.3.2 Allylics

These polyesters are based on the unsaturated allyl alcohol $CH_2=CH-CH_2-OH$ Diallyl phthalates and isophthalates are the most commercially available allylics. Because of the difunctionality of the acid involved, these materials are all thermosetting resins. Allylic resins are normally polymerized by a free radical addition mechanism. Since neither water or other volatiles are formed during their polymerization, low pressure is adequate for their molding and curing.

Glass-fiber-filled resins offer the highest physical strength of all fiber filled allylics. Impact strengths may reach as high as 18 ft-lb/inch of notch. Such compounds are the most dimensionally stable and have excellent properties. Diallyl phthalate compounds filled with Dacron® synthetic fiber are highly shock resistant and offer excellent moisture resistance. Orlon®-filled material is similar to the Dacron® type, except for slightly lower physical properties and heat resistance. Nylon filler normally increases shock and wear characteristics at a slight sacrifice in moisture absorption properties. Asbestos filled compounds have good electrical properties and dimensional stability, and are the most economical.

The material has a number of positive characteristics that are applicable to shelter panel fabrication. For example, the storage stability of the compounded molding materials or prepregs for reinforced structures makes this material a good potential candidate for shelters.

TABLE 30. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOPLASTIC RESINS

Material	Tensile				Comp.		Flexural		Thermal		Impact	Comments
	Ult.	Yld.	Elong.	Mod.	Yld.	Mod.	Str.	Mod.	Cond.	Expan.	Ft-lbs	
POLY-PRO-PYLENE RESINS	4.8 ksi	4.8 ksi	30%	$1.6x10^5$	$5.5x10^3$	-	6.0 ksi	$1.7x10^5$	1.21	$3.8x10^{-5}$	0.4	These resins have resistance to acids, alkalis and salt solutions at normal temperatures. Inherent toughness allows their use as structure elements such as integral hinges. New modifications to the resin system will enhance its use for shelter applications.
POLY-STYRENE RESINS (Med. Impact)	6.0 ksi	6.0 ksi	3.0%	$3.9x10^5$	4.0 ksi	-	-	$3.5x10^5$	0.68	$3.3x10^{-5}$	0.5	These resins have moderate resistance to most alkalis, acids and oils, but not to organic solvents. Modifications and new resins will make them usable as shelter elements such as door frames, etc.
POLY-VINYL CHLORIDE RESINS	[illegible].5 ksi	-	[illegible]%	$3.5x10^5$	10.0 ksi	$4.0x10^5$	11.0 ksi	$3.8x10^5$	1.00	$2.8x10^{-5}$	0.5	These resins and their future modifications show promise for future use because of their resistance to chemical attack by moderately active chemicals. Principal areas of future use will be foamed, extruded shapes, molded tanks and shapes and small ancillary equipment items.
POLY-ALLOMERS	39 ksi	-	350%	-	-	-	-	$1x10^5$	-	-	-	These resins can be used for molded parts that require toughness. Also used as hinges.

TABLE 30. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOPLASTIC RESINS (CONTINUED)

Materials	Tensile Ult.	Tensile Yld.	Tensile Elong.	Tensile Mod.	Comp. Yld.	Comp. Mod.	Flexural Str.	Flexural Mod.	Thermal Cond.	Thermal Expan.	Impact Ft-lbs	Comments
ABS RESINS	6 ksi	-	5-20%	$3.3x10^5$	$10.5x10^3$	-	9.9 ksi	$3.5x10^5$	.007-.015	$3.2x10^{-6}$	2.0	ABS resins have low moisture absorption, excellent resistance to aqueous acids, alkalis and salts by organic solvents such as ketones, esters, aldehydes, etc.
ACETAL RESINS	8.8 ksi	8.8 ksi	at yield = 12%	$4.1x10^5$	$4.5x10^3$	-	13 ksi	$3.75x10^5$	.013	$4.5x10^{-5}$	1.3	Acetal resins have low moisture absorption (.22% in 24 hr boiling water), excellent resistance to strong alkalis and most organic solvents but are slightly affected by aromatic hydrocarbons and glycols.
ACRYLIC RESINS	5.5 ksi	-	25%	$2.3x10^5$	$7.3x10^3$	-	8.7 ksi	$2.8x10^5$	0.01	$4.0x10^{-6}$	0.8	Acrylic resins are excellent optical materials for windows, lenses, etc. Resistant to weak alkalis and acids. Attacked by organic solvents.
CELLULOSIC RESINS												These materials are resistant to dilute (10% conc. acids and alkalis. Not resistant to organic solvents.
-Butyrate MH	5 ksi	--	-	-	5.3 ksi	-	5.6 ksi	$1.2x10^5$	1.74	$6.0x10^{-5}$	4.4	
-Propionate 1	6 ksi	-	-	-	6.2 ksi	-	6.8 ksi	$1.7x10^5$	1.74	$6.0x10^{-5}$	4.4	

TABLE 30. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOPLASTIC RESINS (CONCLUDED)

Materials	Tensile				Comp.		Flexural		Thermal		Impact	Comments
	Ult.	Yld.	Elong.	Mod.	Yld.	Mod.	Str.	Mod.	Cond.	Expan.	Ft-lbs	
POLY-CARBON-ATE RESINS	8.5 ksi	-	10%	$3.5x10^5$	10 ksi	-	12 ksi	$3.1x10^5$	1.40	$1.8x10^{-5}$	4.0	These resins are resistant to attack by weak alkalis and acids but are attacked by organic solvents and strong acids and alkalis.
FLUORO-CARBON RESINS												These four resins are popularly called Teflon® and are essentially chemically inert to attack by corrosive chemicals and organic solvents.
-TFE	3 ksi	-	300%	$0.5x10^5$	1.2 ksi	$0.8x10^5$	-	$0.6x10^5$	1.68	$5.5x10^{-5}$	2.5	
-FEP	7.2 ksi	-	300%	$1.7x10^5$	13 ksi	$1.7x10^5$	-	$0.8x10^5$	1.44	$8.3x10^{-5}$	No break	
-CTFE	5 ksi	-	150%	$2.0x10^5$	2 ksi	$1.8x10^5$	3.5 ksi	$2.0x10^5$	1.74	$3.9x10^{-5}$	3.5	
-Poly-vinylidene fluoride	7.5 ksi	-	250%	$1.7x10^5$	13 ksi	$1.7x10^5$	2 ksi	-	1.68	$8.5x10^{-5}$	3.8	
POLY-AMIDE RESIN												Principal use in shelter applications will be in small auxiliary items such as cabinets, buttons, cordage, etc.
-Nylon 6/6	11.8 ksi	11.8 ksi	60%	$4.75x10^5$	4.9 ksi	-	-	$4.1x10^5$	1.7	$4.5x10^{-5}$	1.0	
-Nylon 6/10	8.5 ksi	8.5 ksi	85%	$2.8x10^5$	3.0 ksi	-	8 ksi	$2.8x10^5$	1.5	$5.0x10^{-5}$	0.6	
POLYETHY-LENE RESINS												These resins have excellent resistance to acids and alkalis making them particularly useful for food handling equipment, water pipe, etc.
- Medium Density	2.0 ksi	-	200%	-	-	-	-	$3.5x10^4$	2.28	$8.3x10^{-5}$	-	
-High Density	5.4 ksi	-	400%	$1.0x10^5$	-	-	-	$7.5x10^{-4}$	2.28	$8.3x10^{-5}$	720	

5.8.3.3 <u>Amino</u>

Amino plastics are thermosetting resins obtained by a condensation reaction between formaldehyde and such compounds as urea, melamine, dicyandiamide, ethylene urea and sulfonamide.

The ureas and melamines are unaffected by solvents and the alpha cellulose-filled melamines and ureas are among the hardest plastics available. Hardness, combined with rigidity and abrasion resistance, allows continuous handling of molded products with no apparent effect on physical properties or appearance.

The resin system is classed as self extinguishing. The properties of these resins indicate a potential as materials for fabrication of rigid panels for shelters.

5.8.3.4 <u>Epoxy</u>

The epoxy (ethoxyline) resins are those which contain an epoxide group. Epoxy resins are generally produced from bisphenol-A and epichlorihydrin. A wide range of these thermosetting resins is available and varies from a low molecular-weighted liquid diglycidyl ether of bisphenol-A, to hard, tough, high-melting solids.

Each terminal group contains an epoxide linkage, and the repeating units contain secondary alcohols; and it is through these that curing (cross-linkage) of the resin takes place. There are many possible types of curing agents, among them the amines, diamines, and the anhydrides. These enter into the molecular structure, and influence the properties of the cured material.

Epoxies have extremely broad capability for blending properties through resin systems, fillers and additives. Formulations can be soft and flexible, or rigid and tough. They are available as solids and liquids in a wide range of viscosities. Formulations are available to cure at room and intermediate temperatures. Others require elevated temperature cure for optimum properties. This versatility leads to wide use of epoxies in many diversified applications.

As an epoxy molding and casting compound the material can be bonded to all metals, most plastics, glass, ceramics, wood, and paper. Epoxies have excellent wettability for adhesion. Adhesive strength of epoxies to a substrate is usually stronger than the internal strength of the resin itself. Adhesion is stable under a wide range of humidity, temperature and chemicals.

Variations of this resin are presently being used in shelter panel fabrication. The material has considerable versatility relative to chemical chain modification and therefore can be tailored to meet the requirements for shelter concepts.

5.8.3.5 <u>Phenolics</u>

The phenolics are the oldest and the least expensive of the thermosetting plastics. The manufacture of a phenolic plastic part first involves the preparation of the pure resin, which is then blended with dye, filler, and other material to provide the molding powder.

Fillers used in typical phenolic molding powders are fibrous in nature, and their interlocking fibers act to reduce brittleness of the resin and to give pronounced reinforcing effects.

The term "phenolic plastics" also includes laminated material where wood, paper, asbestos, felt, glass fibers, etc., may be impregnated and bonded together at pressures in excess of 1000 psi.

Foamed phenolics are made from liquid resin by a chemical blowing process. Large quantities of liberated gas, such as that between an acid and sodium bicarbonate, make a broth of the resin. The heat release of the reaction brings the resin to cure temperature, while the water produced in the curing process is released in the form of steam; the steam also contributes to the volume of froth.

This resin is presently being used as an impregnate for the Kraft paper in existing honeycomb panels of USAF rigid-wall structures. Future use of this material would be as a reinforced phenolic face sheet in place of aluminum face sheets used on existing honeycomb panels and for new shelter concepts.

5.8.3.6 Polyesters.

The polyester resins are those resins with ester groupings as the key links in their molecular chains. They are made by condensation reaction with a dialcohol and a diacid as starting materials. These resins are usually classified into three general types: The saturate polyesters, polyesters with unsaturated acid components, and polyesters with an unsaturated alcohol as a component.

This material has long chainlike molecules characteristic of thermoplastic resins, and can be extruded into fibers such as Terylene® or Dacron® by uniaxial stretching, or Mylar® film which is stronger than any other commercially available film.

There are a wide range of structural properties available for this system and include high modulus and impact strength, combined with excellent flexural and tensile properties.

The material has excellent design flexibility, because stiffness and heat resistance can be varied. In addition, certain polyesters do not require matched molds, heat and pressure for curing. This permits comparatively low cost forming of complex shapes.

The characteristics of the polyester resins indicate a high potential for shelter applications. Because the resins can be easily modified or chemically tailored to develop specific properties, they must be considered as promising materials for the 1980's.

5.8.3.7 Silicones

Probably no class of synthetic material has found so many diverse and seemingly unrelated applications as the silicones. Chemically, the silicones are organopolysiloxanes. The alternating silicon and oxygen atoms which are located in the backbone of the molecule, are common to many minerals such as quartz and mica.

The length of the chain, and thus the molecular weight, can be varied from only a few to several thousand atoms, producing a variety of materials ranging from low viscosity fluids to semi-solids.

A variety of ingredients may be added to such polymers, to further modify their physical form and properties. The fluids may be emulsified; or soaps or inert fillers may be added to form greases. Pigments, fillers and fibers may be added to form resin compounds. Vulcanizing agents and reinforcing fillers are added to very high molecular weight fluids to prepare rubber stocks.

Long-term stability and resistance of silicone rubber to severe environmental conditions are without equal among elastomers. They are highly resistant to oxidation and deterioration caused by heat aging, in addition to their serviceability at very low and very high temperatures. They have excellent resistance to oils and chemicals, superior long-term stability against weathering effects, good radiation resistance as compared to other elastomers, and excellent resistance to water and steam.

Because of a particular outgassing property associated with these materials, additional R&D is required to modify the resin for eventual use as a rigid wall or flexible wall shelter material. Potential use as a shelter material is very high.

5.8.3.8 Urethanes

The basis of urethane chemistry is the reaction of an isocyanate group with the hydrogen of a hydroxyl group, whereby the reactants join through the formation of urethane linkages. Depending on the type of raw materials chosen and in the manner in which they are combined, the products created can take the form of elastomers, foams, and coating resins.

Generally, flexible urethane foams are prepared commercially from polyether or polyester resins diisocyanates and water in the presence of catalysts. The reaction between water and the isocyanates liberates carbon dioxide which functions as the flowing agent to create an open cellular structure.

Rigid foams are manufactured by incorporating fluorocarbon blowing agents (e.g., monofluorochloromethane, difluorochloromethane, etc.) with the reactive polyol and isocyanate combination. The exothermic heat of reaction causes the high molecular weight fluorocarbon gases to boil, and the resulting vapor creates a closed cell foam structure.

By varying reactants, catalysts, and emulsifiers, either rigid or flexible foams with a wide range of properties can be created.

Resins used with the polyisocyanate may be classified as: (1) polyether urethane (based on polyfunctional propylene ether glycols); (2) polyester urethane (based on chemically saturated polyesters); and (3) castor-oil urethane (based on castor-oil derivatives).

The manufacturing process may be classified as: (1) one-shot foams (all raw material combined in one step); (2) prepolymer foams (isocyanate combined with polyester or polyether, then foamed by the addition of catalysts and blowing agents); and (3) semi-prepolymer foams (isocyanate first combined with part of the resin then mixed with the remaining resin and foamed).

This material has a high potential (in a modified form) for use in shelter concepts. The rather high crystallinity temperature is a shortcoming, however, R&D presently in progress may remedy this characteristic. An additional property that must be corrected is the materials tendency to swell when exposed to various solvents.

5.8.3.9 Physical and Mechanical Properties

The physical and mechanical properties of thermosetting resins are shown in Table 31.

5.8.4 Fillers

A filler is any substance, either organic or inorganic, that is blended with a resin to produce a nonhomogeneous mixture than can subsequently be processed by foaming, molding, casting, etc. The primary purpose for adding the filler is to improve the physical and mechanical properties of the material system.

Filler materials can be in the form of:

- Whiskers
- Particles
- Microspheres
- Salts and oxides
- Fibers

5.8.4.1 Whiskers

Whiskers is a term that is used to describe high-strength acicular, single crystals having a large aspect ratio. Whisker material is not new. Because of the unique tensile and modulus properties of whiskers, studies are underway to utilize the properties to enhance plastic, metal, and ceramic structural materials. Figure 36 shows a comparison of the strength to weight ratio (psi/density) of whiskers with other filaments used as reinforcement.

A number of studies have investigated the properties of whiskers and their use for reinforcing resin matrices. The information available is limited to one family of resins, but there is a high probability that whiskers will provide outstanding structural-composite systems for the 1980's. Table 32 shows the results of whisker composites as they are compared to a high strength continuous S-glass composite.

The strong potential for whisker composites is clearly indicated by comparing the specific modulus and specific strengths shown previously in Table 26. However, the glass composite is a material which can be fabricated into shapes today, whereas at the present time, whisker composites have manufacturing problems yet to be solved. It is apparent that proper resin matrices for these new materials must be selected for their mechanical properties, by

TABLE 31. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOSETTING RESINS

Materials	Tensile, ksi				Comp., ksi		Flex		Thermal		Impact	Comments
	Wt.	Yield	Elong	Mod	Yld	Mod	Str ksi	Mod 10^{-6}psi	Cond (1)	Expan (2)	Ft-Lbs	
Alkyds	7.5	-	-	-	20	-	20	2.2	0.2-0.3	6-7.5	10	Although this mat'l is expensive, it has excellent fungus & solvent resistant & dimensional stability
Alkylics (pre-polymer)	4.3	-	-	0.5	25	-	8.0	0.5	-	-	0.25	Excellent characteristics in area of corrosion, fungus & solvent resistance. Very low cost.
Amino	5.0	-	-	1.4	42	-	11	1.0	-	17	0.14	Self-extinguishing & unaffected between -70°F to 210°F
Epoxy (Rigid)	10	-	-	3.0	25	-	15	-	1.4	11	4.0	Has excellent strength, stability, casting characteristics & chemical resistance & weatherability
Phenolic	8	-	16	1.5	20	-	20	1.2			0.25	Excellent all around material, relatively inert to environment
Polycater	10	-	3	-	20	-	20	2.0			0.4	Has a wide range of properties that are dependent upon the starting compounds. Relatively good mat

TABLE 31. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOSETTING RESINS (CONCLUDED)

Materials	Tensile, ksi				Comp., ksi		Flex		Thermal		Impact	Comments
	Wt.	Yield	Elong	Mod	Yld	Mod	Str ksi	Mod 10^{-6} psi	Cond(1)	Expan(2)	Ft-Lbs	
Silicones	3.5	-	-	-	14	-	6				0.3	Fairly good all around, however solvents tend to swell & distort the the polymer chain.
Urethanes	7.5	-	600	1.2×10^4	20	-	1	0.08	1.0	-	-	Same as above (silicones) however, properties are very good.

(1) BTU/Hr/SF/inch/°F
(2) 10^{-6} in/in/°F

TABLE 32. COMPARISON OF WHISKER-REINFORCED PLASTICS WITH HIGH STRENGTH GLASS REINFORCED PLASTICS

Property	Epoxy + Si_3N_1 (35%) (21)	Epoxy + Al_2O_3 (14%) (23)	Epoxy + S-glass (70%)	Epoxy + S-Glass (14%)
Specific Gravity S.G.	1.90	1.64	2.11	1.38
Modulus E, psi	15×10^6 [a]	6×10^6 [d]	8.9×10^6	
Strength, Sc, psi	40,000[b]	113,000	300,000	75,000[c]
Specific modulus E/S.G.	7.9×10^6	3.65×10^6 [d]	4.2×10^6	
Specific strength Sc/S.G.	22.2×10^3 [b]	69×10^3	140×10^3	54.5×10^3

[a] Assuming all whiskers are parallel; modulus for the mat reinforced was 5×10^6 psi which gives a specific modulus of 2.6×10^6 psi.

[b] This value reported for 30% whisker content and this was accounted for in calculating specific modulus.

[c] This strength was calculated based on utilizing 70% of the glass virgin strength

[d] Using the potential modulus of 8.8×10^6 psi, the specific modulus would be 5.35×10^6 psi.

the viscosity of the uncured resin, wetting characteristics, adhesion to the filament surface and cure characteristics. Resins can be formulated with the proper mechanical properties to optimize composite behavior and there is a high probability that the manufacturing problems will be solved before the time frame of interest.

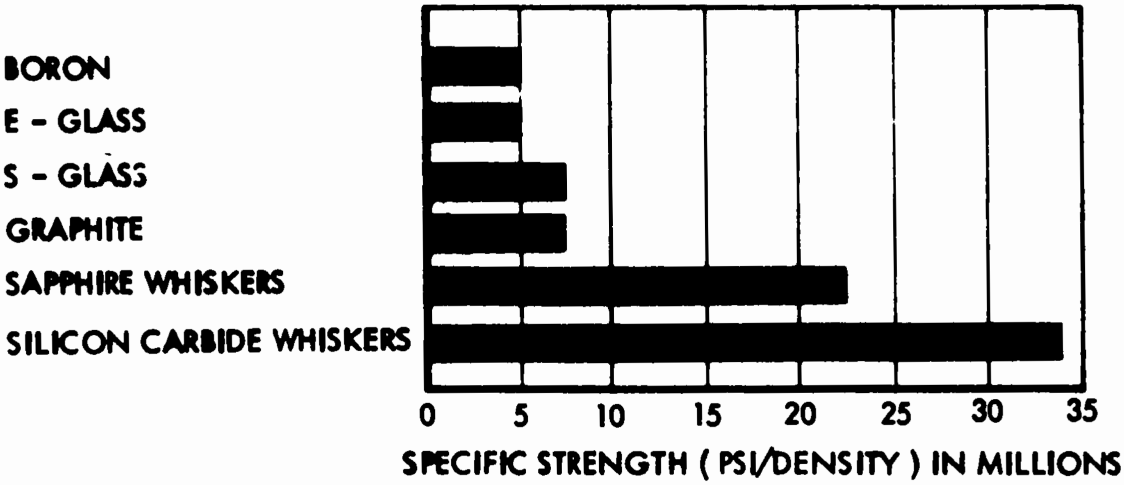


Figure 36. Comparison of Specific Strengths for Whisker Materials

5.8.4.2 Particles

Sand, quartz, tripoli, and diatomaceous earth are naturally occurring forms of silica which differ in particle size, degree of crystallinity, and hardness. Large volumes of graded silica sand are used with small proportions of resin in the shell molding process, and in resin cements. Sharp silica sand is often spread over uncured surfaces of resin cements to provide an abrasive surface.

Naturally occurring quartz has been used as a filler with phenolic and epoxy resins to provide ablative insulators for nosecones, space capsules, and rocket motors. A quartz-epoxy resin composite with 60 percent filler has a linear coefficient of expansion value comparable to that of aluminum or brass.

5.8.4.3 Microspheres

Hollow glass spheres called Microballoons may be added to resins in programmed concentrations to produce syntactic foams of controlled specific gravity. Ceramic and phenolic resin Microballoons and thin-walled carbon spheres may also be used.

Composites of resins and solid glass spheres are characterized by high modulus and good flexural and compressive strength.

Multicellular glass nodules with diameters of 1/8 to 1/4 inch also improve molding operations without increasing the density of the finished product. Some reinforcement is noted when these spheres are treated with silane.

5.8.4.4 Salts and Oxides

Zinc oxide - polypropylene composites have excellent resistance to weathering. Aluminum, magnesium, and titanium oxides give increased stiffness, hardness, and resistance to creep to composites. High thermal conductivity is obtained when 70 percent by weight of beryllium oxide microspheres are added to epoxy resins before casting.

Berium sulfate is used as a filler and white pigment in polyvinyl chloride films which are opaque to x-rays. Grinding devices may be produced by dispersing finely divided silicon carbide in the premix used to cast polyurethane foams. Products with antifrictional qualities are obtained when finely divided molydenum disulfide is added to elastomers. A composite of berium ferrite to polyvinyl chloride has magnetic properties.

5.8.5 Fibers

Fibers have two different and distinct applications to advanced shelter concept elements. The fibers can be woven into a fabric or chopped for use as a filler for resins. Both of these applications will be discussed.

A number of materials have a high potential of being available for fillers in the 1980's. This high probability is attributed to the level of research effort being expended toward the fiberizing of high temperature resistant, high-strength and high-modulus materials. Examples of such fibrous materials are aluminum oxide, zirconium boron nitride, polyimides, tungsten, stainless steel, polybenzimidazole, carbon, graphite, boron, aramid, carbide, silicon carbide, and the recently developed poly (bisbenzimidazophenanthroline). The potential of these fibers for the 1980-1990 decade lies in their response to load environment and in the fact that they possess the properties necessary for use as reinforcements in structural composites. Of particular note for this application are the aramids.

5.8.5.1 Aramids

This fiber material was introduced commercially in 1972 and has a high probability of being used in composite material systems for rigid and flexible wall shelters. This high probability is based on the present status of product development and the level of availability of the basic polymer.

The two aramids of interest to future shelters are Kevlar® and Nomex®. This family of materials is resistant to the various solvents that would be used during deployment. Kevlar® is limited by a compressive strength that is not as high as other fibers; however, if this physical property is necessary, a blend of graphite refractory oxide or boron fibers with a selected resin matrix can be used to increase the compressive strength.

One of the previous fibers, Kevlar®, has the most promise for incorporation in panel or honeycomb structural matrixes for the 1980's.

The basic characteristics of Kevlar® that make it extremely interesting for use in shelter concepts are:

- Filaments can be drawn to diameters as small as 0.4 mil permitting several to be incorporated into threads for weaving into fabrics having controlled directional properties.
- The 0.4 mil diameter filament permits weaving a fabric having a fine denier.
- Low density, 0.050 lb/cu in., half that of aluminum.
- High modulus, 20 million psi, twice that of aluminum.
- Low cost in production quantities.
- High strength composite, 240,000 psi, 3.5 times that of aluminum.
- Usable up to 460°F.
- Electrical properties equivalent to fiberglass.
- Fire resistant, similar to Nomex®.
- Handles well, extremely high toughness and impact resistance.

5.8.5.2 Nylons

These fibers are formed from long chain synthetic polyamides having recurring amide groups as an integral part of the polymer chain. A newer nylon called Quiana may prove to be an excellent addition to the fabrics used in layups for composite structures. The Quianas provide excellent resistance to sunlight.

5.8.5.3 Acrylics and Modacrylics

The present use of Dynel® in tent structures is a firm indicator of the potential use of a modified Dynel® (acrylonitrile vinyl chloride). The modacrylic (Vernel) and Dynel® materials are self-extinguishing.

5.8.5.4 Polyester

The polyester fibers are composed of at least 85 percent of an ester, dihydric alcohol and terphthalic acid. This family of fibers has in recent years had the greatest degree of research and development with respect to chemical chain modifications and types of additives used for impregnating the roving.

5.8.5.5 Novoloids

Novoloids are a new generic fiber class. They are man made fibers containing at least 85 percent by weight of cross-linked novalaes.

The novoloid fiber marketed to date is trademarked Kynol®.

Kynol® is an obvious candidate for flame resistant shelter applications. When incorporated into the phenolic resins, the fiber provides a composite system for shelters of the 1980's.

5.8.5.6 Graphite

High-strength graphite fibers for advanced composites currently are under intensive research and development. These filaments, produced by the controlled pyrolysis of organic fibers, have a theoretical maximum strength of 140 million psi. The best commercially available material has a strength of 75 million psi, although graphite fibers with strengths over 100 million psi have been produced in research quantities. The processes that are used to manufacture graphite fibers show a significant potential for cost reduction.

Most research and development has focused on the use of epoxy resins in conjunction with graphite because of their generally good overall strength, resistance to chemicals, and a well-funded library of technology. Some work has been done with polyesters, polycarbonates, polypropylenes, silicones, and other polymers, but none of these appears to offer the overall advantages of the epoxies. High-temperature polymers, however, because of the 302°F temperature limitation of epoxies, are currently being investigated. The most promising are the polyimides, but others, such as polybenzimidazole, polythiadiazole, appear to have some promise.

Table 33 presents some data relative to the physical properties of this fiber and composite system.

TABLE 33. GRAPHITE COMPOSITE SYSTEM CHARACTERISTICS

Fiber	Percent Weight Epoxy Resin	Percent Volume Fiber	Density g/cc	Tensile Modulus 10^6 psi	Flexural Modulus 10^6 psi	Flexural Strength 10^3 psi	Shear Stress 10^3 psi
[illegible]	[illegible]	[illegible]	[illegible]	22.1	23.2	[illegible]	[illegible]
[illegible]	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Type II	[illegible]	[illegible]	[illegible]	[illegible]	19.8	[illegible]	[illegible]
Type 100	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
[illegible]/cont	[illegible]	[illegible]	1.58	-	[illegible]	119.6	[illegible]

Graphite fibers are relatively soft, so that graphite/polymer composites can be formed and machined easily. They are a small diameter fiber and can be fabricated by glass fiber technology. Some of the problems occur when attempting to obtain a satisfactory bond between the fiber and the polymer matrix. Poor abrasion resistance of the graphite fiber also presents a handling problem.

5.8.5.7 Glass

Although glass filaments are considered the grandfather of composite materials, it required the success of boron to revive an interest in glass for advanced composites. Glass theoretically is an extremely strong material and current research is producing glasses that achieve much of this theoretical strength. S-glass, with a modulus of 12.5 million psi and a tensile strength of 600,000 psi, now is in common use in advanced composites. An even newer glass filament material developed by the Air Force, 970-S, has a tensile strength of 800,000 psi and a modulus of more than 15 million psi. Recently, 11 glass compositions with modulus values over 20 million psi and another 24 in the 18 to 20 million psi range have been developed.

The vast majority of research, development, and use has centered on polymer matrices. Metal matrices are distinctive by their absence and only a little effort has been expended on ceramic matrices. Polymer matrices have included almost every material available from acetals and epoxies to polyesters and polyimides. Most of the specialized applications use an epoxy resin matrix. Glass itself is a ceramic and would be naturally compatible with ceramic matrix materials. For this reason, some current research is underway in glass/ceramic composites.

The properties of this readily available material are surprisingly high, to 80 percent of the tensile strength of the virgin filament. S-glass/epoxy cylinders have shown tensile strength of 500,000 psi. Surface defects on the glass filament can significantly reduce the final composite strength. This effect decreases with decreasing filament diameter. Pressure vessels made with the new 970-S glass/epoxy composites show tensile strengths that are 20 percent higher than comparable S-glass composites. Modulus also is higher, about 15 percent. Glass composites, of course, exhibit relatively poor strength characteristics in compression. Crossply filament winding of composites normally is used to eliminate this poor compressive composite strength. Glass composite technology is well established. Filament-winding equipment is readily available and very large structures can be built in glass/polymer composites. Glass filaments are less costly than other reinforcing filaments used for composites by a factor of about 100. Glass filaments are wetted easily by most polymers and glass exhibits very good compatibility with almost all polymer systems currently in use. Filaments are quite flexible and composite structures can be designed with relatively small radii. Present glass strengths still are capable of being improved significantly with only nominal cost increases when compared to other advanced composite reinforcement costs. A problem associated with glass filaments and unidirectional composites is that they are relatively poor in compressive strength. Glass filaments also lack the stiffness that can be obtained in other materials, such as boron. Modulus of present glass filaments and fibers is significantly lower than other materials, such as graphite and boron.

5.8.6 Structural Foams

Structural plastic foams have specific properties that can find direct application to shelter systems for the 1980's. The types of materials that can be considered as structural foam are simple to define. Virtually any plastic that can be injection molded or extruded can also be produced as a structural foam by any of the numerous methods that have been developed. The major exceptions include thermosets and those thermoplastics that have very high melting temperatures.

The advantages of these types of foam systems are the high stiffness to weight ratio, stress-free molding and low cost. The insulative characteristics are superior to the resin/fiber composite member.

The laminar structure of a structural foam part is somewhat analogous to an I-beam. Strength is not only dependent upon density, but also changes with wall thickness. The thicker the section, the less the I-beam effect. In addition, the engineer also has the ability to change skin thicknesses by changing processing conditions. Of the plastic foams now available, the most rigid, Figure 37, are the glass fiber reinforced polystyrenes, nylons and polypropylenes, and the unreinforced polycarbonates. Thermoplastic polyester foams, which should become commercially available about the middle of 1975, are more rigid than any other unreinforced plastic foam material.

The high stiffness to weight ratio of the foams compared to those of metals means that less material can be used to obtain equivalent stiffness, Figure 38. However, it is important to note that as the thickness of structural foam increases for a specific density, the stiffness, as measured by flexural modulus or elastic modulus, decreases.

Because of the relatively weak core, structural foam generally is not recommended for use in tension. Flexural and compressive strengths of the materials, however, are relatively high. The materials are used in many applications where high compressive and flexural loads must be withstood.

Although all the types of thermoplastics now being foam molded are available in self-extinguishing grades, few of the foam molding grades have this characteristic. Self-extinguishing structural foams are: polyurethane, polycarbonate, Noryl phenylene oxide based material, and nylon. The flame retardant additives used with the other plastics either adversely affect the foam molding characteristics of the resins or they cannot withstand the thermal cycling requirements of the structural foam molding methods.

An improved flame retardant polycarbonate is being developed and it is most probable that flame retardant foam materials will be available for the 1980's.

The relative low cost of the structural foam materials are an additional plus for using this type of material for short-term shelters.

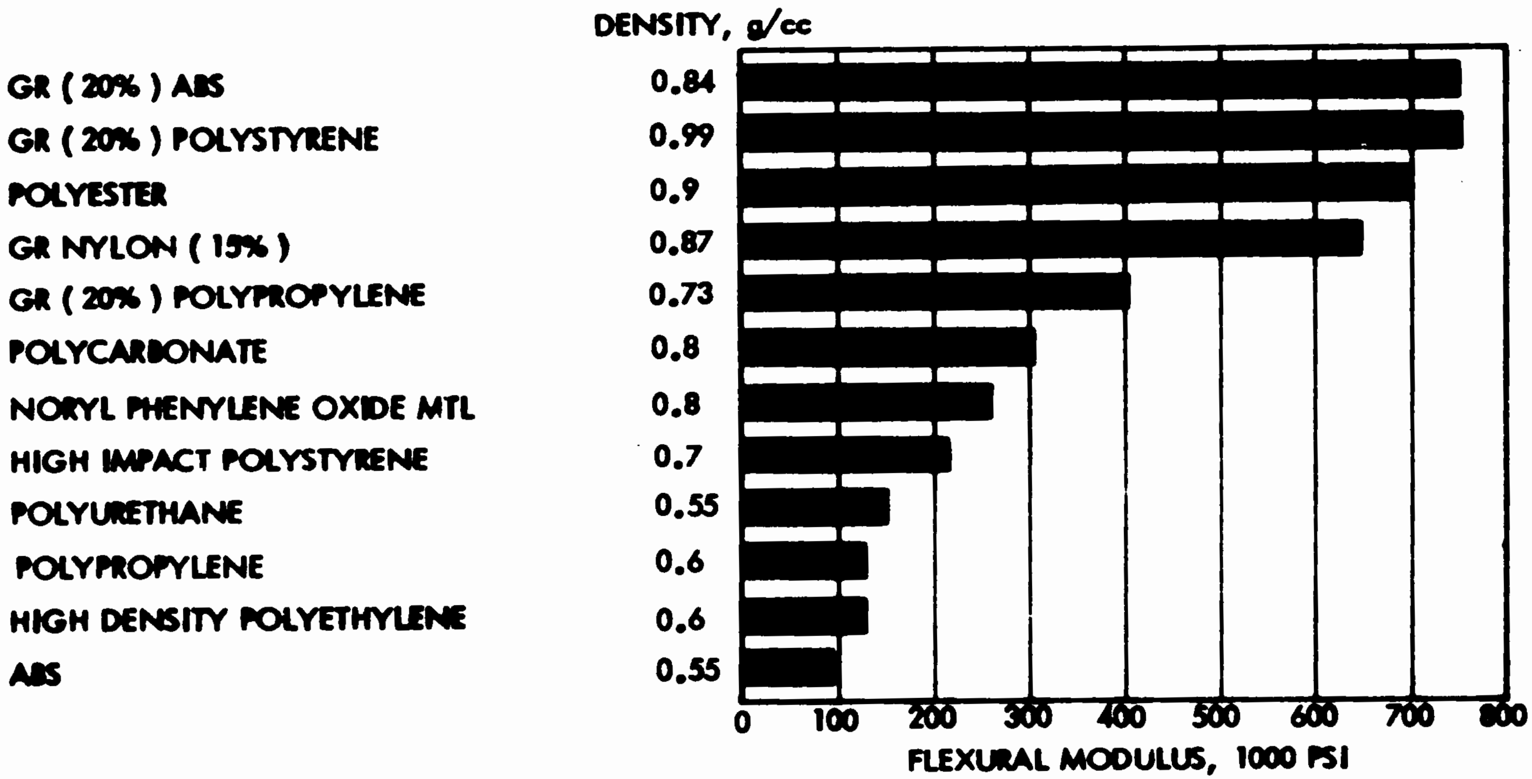


Figure 37. Flexural Modulus of Rigid Foams

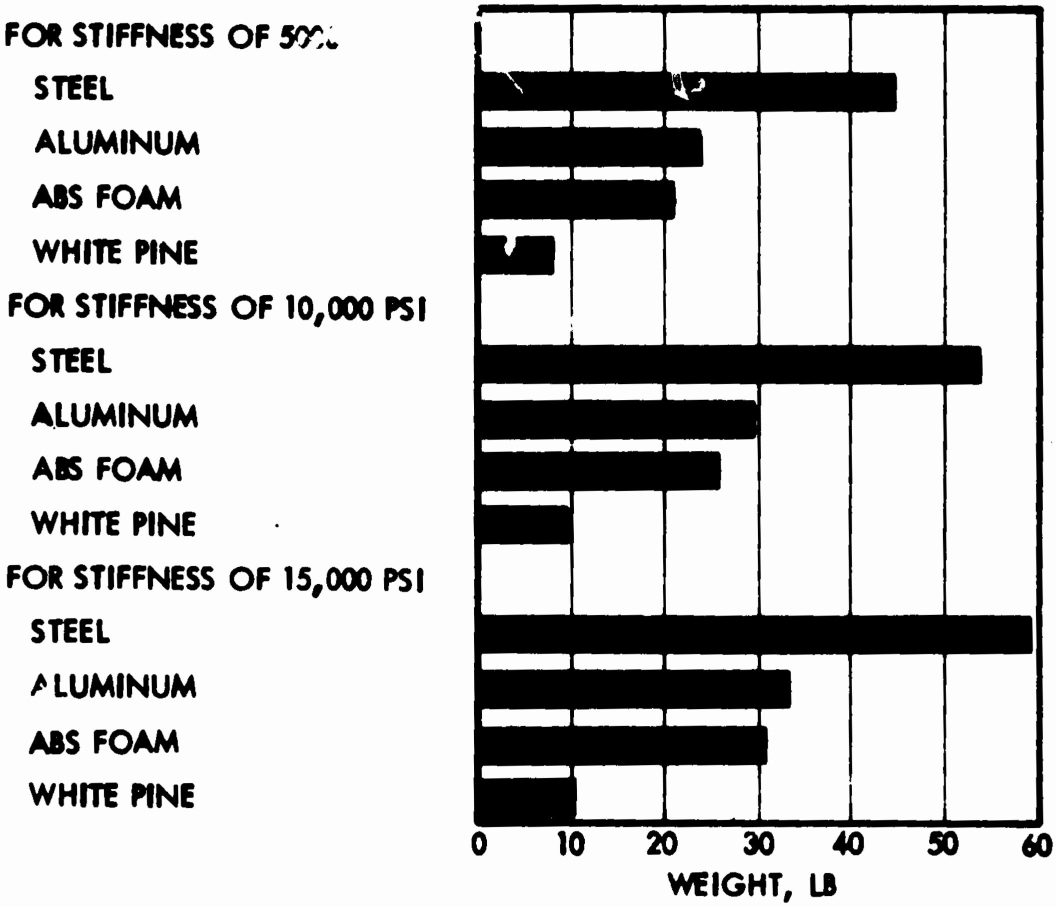


Figure 38. Comparative Stiffness to Weight Ratio of Plastic Structural Foams, Metals, and Wood

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

The majority of the shelter concepts are very good as regards shape, weight, expansion ratio, simple and rapid erection methods, adaptability to diverse uses, routine maintenance, safety, and compatibility with various transport systems. Current shelters are somewhat deficient in actual performance in the areas of durability in deployment or storage, damage resistance, repairability, provisions for passive defense, overall efficiency of environmental control of interiors, compatibility with extremes of climate, and compatibility with commonly-available site conditions.

The deficiencies identified are primarily due to limitations of the materials and manufacturing techniques utilized, which seem to have been made primarily on a low-first-cost basis, and also due to current limits of material performance. Existing overall shelter concepts are amendable to having deficiencies corrected by (1) application of improved fiber-reinforced plastic materials forecast for availability in the 1980's, and (2) use of advanced manufacturing techniques.

A representative list of currently-in-development (or in-limited-use) materials and processes that are recommended for consideration for shelter applications is as follows:

1. Epoxies, polycarbonates, and polyester resins reinforced by graphite fibers, metallic oxide fibers, aramid fibers, and glass fibers, layed up by automated tape laying machines, tape winding machines, or pultruded; usage would be as replacements for sandwich panels.
2. Chopped-fiber-reinforced epoxies or polycarbonates, compression-molded; usage would be as closeouts, window frames, and high load points on panels.
3. Foamed epoxies, polycarbonates, polyesters, and polyurethanes reinforced by chopped fibers; usage would be lower-stress-level structural panels.
4. Ultra-high-molecular-weight polyethylene moldings for fittings, bearings, and wear-points.
5. Woven aramid fabrics for large-scale layups, fabric external covers, ropes, and interior structures such as integral shelves, suspended ceilings, and load-carrying utility ducts; and for selective reinforcement of foamed panels and ballistic-protection covers.
6. Elastomer-based spray-on flexible coatings, filled with asbestos, metal fibers, or other fillers for special purpose coverings.

Additional performance improvements in deficient areas of existing shelter concepts can also be achieved by (1) using more conservative design allowables for strength and stiffness, and (2) more conservative assumptions regarding material performance, durability, and service life in extreme environments.

If shelters are redesigned with these philosophies, the resulting designs might tend to be excessive in weight and cost, using today's materials. However, forecast increases by the 1980's specific strength and specific stiffness in commonly and economically available structural materials can be utilized to counteract weight increases.

Cost increases can be counteracted by the more extensive use of common panels and other structural members, more extensive use of molded or automated layup structural elements that include integral stiffeners, fittings, joints, openings, etc.

In the cases of extreme-climate compatibility, provisions for passive defense, EMI control, and site compatibility, it is recommended that supplementary kits be provided to perform these functions in the form of disposable foundation kits, disposable hangar floor kits, strap on and reusable covers for thermal control, EMI control, and ballistic penetration resistance.

In addition, while most basic shelter concepts can be designed specifically to meet almost any present or proposed transport/handling system, it is also concluded that a supplementary shelter container/pallet kit would be very useful to carry other kits such as floor kits, foundation kits, and spare parts.

While current shelters (such as Bare Base and other military shelters) could be beneficially redesigned by using the material substitution approach, a revised shelter family which uses a greater percentage of common panels could make better use of any or all of the above mentioned design approaches. The new shelter family would consist of personnel shelters and shop/administrative shelters that would be shaped and sized to use the same panels used to construct the hangar and storage buildings. The potential penalty in erection complexity for the smaller shelters (compared to the current Bare Base Expandable Personnel Shelter and Expandable Shelter Container) would be counteracted by the first cost and field replaceability benefits of using common panels.

The evaluation of currently available shelter systems indicates that a supplementary shelter kit that uses solar panels and which contains heat pumps, air-cycle refrigeration units, and air filtration equipment would be valuable.

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