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SUMMARY OF DATA AND DESIGN EVALUATION OF SANDWICH CONSTRUCTION APPLICABLE TO MOBILE MILITARY SHELTERS

Alex J. Reynolds

FOREWORD

This technical report represents the author's views and opinions concerning use of composite materials (Sandwich) in the construction and fabrication of mobile military shelters. The discussions within this report are applicable to shelters that require attached mobilizers which do not fully support the shelter underside. These are predominantly in use today and apparently will be used in future programs.

The information herein contained reviews the general past history of sandwich construction and incorporates observations of past programs which revealed specific difficulties and deficiencies of construction.

This report is intended to be used as a guide for those organizations which have a need for lightweight-high strength shelters. It is not the intention of this article to degrade any specific construction techniques but rather to point out construction areas of vital concern which should be critically considered.

This report is oriented to construction requirements that must be tailored to specific military specification parameters. All applicable techniques presently in use today may not be specifically discussed in the report, however, observations to date definitely indicate particular shortcomings in design.

Progress in sandwich construction today is extremely competitive, and use of new materials and adhesives may offer end items which are both reliable and efficient.

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ABSTRACT

The need for transportable shelters today is quite apparent as one considers the complexity of systems requirements in the field of communications, reconnaissance, and interpretation. Field use of such units requires exceptional strength while possessing optimum lightweight characteristics. Sandwich construction offers these characteristics. The common cores presently in use are paper honeycomb and modified polyurethane foams. Both types of cores are in use and both types of construction exhibit some poor qualities that are inherent in each. The author wishes to point out the principal design parameters that should be of concern to those interested in details of such type construction. The best criteria of shelter evaluation is an established test program followed by visual observations after field usage relative to operating time. The presentation herein includes the two basic panel constructions (honeycomb and foam), their merits and limitations, their application and design requirements within the state-of-the-art today. Strictly speaking, the foam construction with structural members is not in the true sense a sandwich. It is a combination sandwich, and internal members.

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SECTION A

INTRODUCTION

The primary purpose of this report is to review sandwich construction as applicable to honeycomb and plastic cores. This summary includes the experiences gained from observations of such type structures subjected to field use as well as prototype and production units under various test programs. It should be understood that this summary includes opinions of the author and establishes a conclusion that is both timely and relevant to military procurements of shelters. This report is being especially written to support test program procedures as a check on designs. Complementary to testing is the need for information obtained on units that have had field usage. Tests and actual time duration of exposure to all forms of environment usually are the best criteria for prediction on performance. To insure that adequate and trouble free performance is obtained, it is therefore essential that all factors contributing to the basic physical effects of temperature, water, wind, stresses, strains, and vibration are considered with relation to time exposure. This report covers significant aspects of work in this field that has been conducted in the last decade.

SECTION B

SHELTER CONSIDERATIONS

1. OBJECTIVE

The major considerations that must be taken into account when considering honeycomb sandwich design are the WATER ENTRAPMENT and delamination problems that may occur after constant field application. Recognizing that failures and unsatisfactory field reports do, at times, conflict with theoretical design predictions, the need for test programs become apparent. Inasmuch as the use of Kraft paper honeycomb type cores appear to be coming back into shelter use, it is completely justifiable that users fully realize the damaging effects of water in paper honeycomb cores. It should be stressed however, that paper honeycomb cores can be efficiently used in a multitude of various applications. Minor as well as major differences in design capabilities will be brought out in a later section.

Both honeycomb and plastic foam cores are herein discussed to acquaint the reader with previous performance characteristics. Without proper design, quality control, testing, and field evaluation over a given period of time, certain risks are being taken that can substantially increase initial manufacturing costs by virtue of required increased maintenance. The major problem with sandwich honeycomb would most likely be WATER MIGRATION which is not inherent in the unicellular foam type panels. Some uncertainty and risk is encountered when individuals believe that panels can be manufactured and guaranteed to be hermetically sealed, and maintain that seal under all environments and imposed mobile conditions.

2. HISTORY

The introduction of highly mobile lightweight shelters into the military inventory to house ground electronic equipment required design considerations of the physical forces that deployment and usage dictates. The mobility requirements for shelters often expose these units to cyclic and secondary stresses which are important in structural work. The bonding of a variety of materials to produce a sandwich invariably imposes important roles on the use and type of adhesives involved. The final item must be of a durable nature, somewhat elastic, and possess high retention of its shape and size. Careful consideration of details is therefore required in the design so that the sandwich structure (shelter) functions so as to meet present military specifications. The application of forces to such structures, which tend to produce cracks or separation permitting the entrance of water, is likely to lead to significant damage that may eventually become a substantial failure. The availability of new materials or new forms of old materials such as a sandwich structure led to development of lightweight military shelters. The so called helicopter liftable shelters were originally designed around 1953. At that time various companies strongly competed in the shelter manufacturing arena. Initial structural success was not immediately obtained till after exhaustive testing periods. During the period of evaluation of various types of shelters, the use of foam over honeycomb was generally adopted as the material most likely to meet with success following disclosure of particular consistent panel failures. Generally, water absorption into paper honeycomb type panels was quite evident. Consistent delamination was prevalent which was a direct result of deterioration of the honeycomb core. Examples of panel failures were observed on a honeycomb Aeronca shelter which was tested at RADC. A prototype modular shelter of honeycomb also possessed inherent delamination problems. Project Four Wheels also contributed to the general swing from honeycomb to foam core types. Detrimental water absorption effects in honeycomb were also evidenced at ERDL and at USASRDL.

To emphasize the injurious effect of moisture on honeycomb, an actual case was reported as follows:

During dehumidification tests on an environmental controller, a Project Two Wheels shelter was used as the controlled area. The shelter had been used in the field, but showed no evidence of panel damage. The panels were constructed of honeycomb paper sandwich between aluminum skins.

The specific test being conducted was to maintain 80°F and 50% Relative Humidity in the shelter with an outside ambient of +125°F and 29% Relative Humidity. The environmental controller reduced the sensible heat temperature to the required +80F, but the relative humidity would not reduce to the required 50%. Condensate from the evaporator was flowing through the overflow pipe, but the Relative Humidity remained constant. The environmental controller was completely checked: Refrigerant pressures, blower RPM and the expansion valve. All were within operating tolerance. The only source of moisture left was in the shelter itself. Panels, seams, access ports, etc., were examined without disclosure of any abnormal condition. Finally, a hole of approximately 2 inches in diameter was bored through the outside skin of a wall panel. Investigation showed that the honeycomb material was saturated with moisture and crumbled under minor hand probing movements. Water was visibly present.

No attempt was made to explain how the material became saturated but substitution of another like shelter resulted in achievement of the required inside conditions.

Such results, and other similar information gathered at the time, resulted in a tendency to use foam as the basic core material instead of pursuing the use of honeycomb. Foam, being unicellular, exhibited no appreciable water absorption deficiencies and possessed high insulative characteristics.

Foam has been used to a greater extent until recent resurgence of use of honeycomb. New adhesives and better control techniques used today may therefore at some time contribute to successful honeycomb shelters. Time and usage may prove their full potential; however, the use of foam construction is recommended until such time as honeycomb units are standardized. The foam units, as being produced today, offer the most advanced lightweight high-payload mechanical structure designs and techniques which have successfully proven their ability in field service operations of all kinds. This type of monolithic construction made of aluminum skins bonded continuously with epoxy resin and welded to an integral frame is, to date, the best possible lightweight structure meeting most of the severe test requirements of military specifications.

The use of other shelter panel constructions has been quite limited. Balsa cores, sponge rubber type cores and even the well-known honeycomb core panels have not been predominantly used for shelter applications. As a result of the many test programs conducted in the early years of evolution of these shelters, performance requirements today, for almost any shelter, revolve around specification MIL-S-52059.

3. PRESENT DESIGN CRITERIA

Requirements for transportable shelters which house all sorts of equipments involved in communications, reconnaissance and intelligence, and data processing, are normally established by the military users in conjunction with engineering assistance from appropriate government agencies. The hardware that is normally produced as a result of specifications developed from requirements, improves with time and usage. As deficiencies develop, the particular problems are dealt with accordingly and improvements are made through specification changes. Current specifications on shelters are therefore an accumulated refinement of initial work which was governed by structural engineering analysis based on engineering assumptions. These specifications for shelters, as we know them today, are optimum in design and possess stringent requirements that we know can be met. A list of these requirements is presented so that the reader may become acquainted with the governing factors that contribute to an essentially reliable shelter as dictated by current requirements. These requirements may differ slightly for the different services; however they are a representative sample of the basic design needs to satisfy most users.

Four basic requirements must generally be fulfilled in the actual design; these are as follows:

a. Structural Design

b. Thermal and Noise Transmissibility

c. Electromagnetic Shielding

d. Transportability

Structural Design

There are several types of loads that are imposed on shelters which they must withstand without degradation. These loads are the static loads imposed by ice and snow and the internal equipments and also the static and dynamic loads caused by constant and buffeting winds. Included also are the more critical dynamic loads encountered in transportation. These transportation loads will be reviewed under the transportability section.

The following requirements are therefore those which have been established and are consistently used:

(1) Ice Load - 2 inches of glazed ice measured radially to all exposed surfaces.

(2) Snow Load - 40 pounds per square foot (normally applied to roof surfaces).

(3) Wind Load - 87 knots (100.14 mph) unguyed and 109 knots guyed.

(4) Floor Load - 150 lb/per square foot (uniformly distributed) and 250 lb concentrated loads (specified over a small area).

This floor loading is commonly used for shelters in the 8' x 8' x 12' size and has been established for payloads up to 5000 lbs. The floor load specified can adequately support 14,400 pounds without any consideration of factor of safety involved for the size shelter indicated. It was evident that equipments within these units normally approached these loads and therefore set this criteria, supported, of course, by physical testing.

It should be noted that in the wind load requirement, the specification of 87 knots for the unguyed condition is slightly misleading. The condition that actually determines whether guying or anchoring is required is the resisting moment to overturning. The resisting moment is a function of the equipment load and center of gravity within the shelter. If the load is light, then invariably guying may even be necessary at wind loads of say 60 knots. Sliding may also occur when total loads are evaluated against wind loads. Air in motion possesses considerable kinetic energy and is usually defined as the product of one-half the air density and the square of the resultant design velocity (in this case 100 mph). To illustrate the force exerted on the side wall of an 8' x 12' shelter, the wind pressure may be calculated from the mathematical expression

$$Pw + .0042\ V^2 \quad \text{where V is in mph}$$

This expression takes care of the shape coefficient and its simple deviation is not included. However, the constant .0042 is a generally accepted conversion factor for flat plates as exhibited by a shelter wall 96 square feet in size.

It is readily seen that for a 100 mph wind the exerted pressure per square foot is considerable:

$$Pw = .0042 \times \overline{100}^2 = 42\ \text{lb/ft}^2$$

which leads to a 4032 pound force acting on the 96 square feet of exposed wall surface.

For world-wide use application, the structure should withstand temperatures of -65°F to +160°F and inherently must possess resistant characteristics to salt fog, fungus, sunshine, sand and dust and humidity as specified in MIL-STD-810.

In summation, and in addition to requirements of mobility, environment, electrical, etc., the mechanical requirements are numerous and severe and must be met under all kinds of conditions the equipment may encounter. These requirements as employed under most military specifications include such tests as:

(1) Shelter drops; flat side, corner and rotational at (a) Room temperature, (b) low temperature (-65°F) and (c) high temperature (160°F).

(2) Transportability

(3) Rail Transport

(4) Vehicular Transport

(5) Three-point suspension

(6) Fording

(7) Air Tightness

(8) Overall coefficient of heat transfer

(9) Lifting and towing eye tests

(10) Door, roof, access steps, hardware and mounting member load tests.

Thermal and Noise Transmissibility

The overall "U" factors that are obtainable today generally range from 0.30 to 0.35 Btu/hr./sq ft./°F and are a function of the shelter design with respect to materials used. Honeycomb, when filled with shredded foam, may attain these exact foam values. The number of openings, louvers, doorways, inlets and other functional features does have an effect on the overall heat transfer value when comparing shelters. It is obvious that the better the insulating medium and the lower the overall "U" factor of the structure, the less heat will be gained or lost to the external air and in effect will reduce the problems of temperature control.

The transmission of noise, both within and external to the shelters, always poses a difficult problem to cope with. The confined areas generally associated with shelters and the emitted noises are a consistent source of aggravation to the human operators. Noise will be simply treated in another part of this report; however, for information, interior shelter noise level requirements are presently restricted to those shown in Table A below:

TABLE A
NOISE LEVEL REQUIREMENTS

Octave Band Center Frequencies (cps)	Octave Band Sound Pressure Levels (In Decibels Ref 0.0002 dynes/cm^2)
63	87
125	77
250	68
500	61
1000	58
2000	55
4000	53
8000	52

Electromagnetic Shielding

Requirements for shielding generally vary based on the need for shielding resulting from the type of operation being performed. Shielding is usually required to protect equipment within the shelter from externally generated signals or to protect internally generated signals from being emitted out of the shelter. Shelters are generally shielded to at least 60 db over a frequency range of 150 KC to 10,000 megacycles. This is inherently obtained through todays construction techniques. Higher attenuation requirements, however, will impose greater penalties such as increased weight and cost. It is felt that equipment shielding with a moderate demand on shelter shielding would be more effective. Shielding characteristics are highly vulnerable to change since continuity of external skins and door closure pressures (20psi) MUST BE maintained at all times. Shielding also incorporates use of filters and necessary attenuation required for all openings including cable interconnections, and junction areas. Shielding requirements are covered under MIL-STD-285.

Transportability

Transportability requirements perhaps impose the severest of actions which involve impacts, shock, and vibration. The shelters must withstand the shock and vibrations as imposed by Cargo aircraft, helicopters, railroads and road transportation. In railroad humping at 9 miles per hour approximately 30 g's of force are imparted to the test item. In 18 inch flat and rotational drops recordings of 25 to 40 g's have been established for payloads in the 5000 pound range. These tests all simulate, as closely as possible, the conditions expected to be encountered. Vibration and shock criteria applicable are subject to meet the rigorous standards of MIL-STD 810.

There are other practical considerations that have been introduced in the shelter design field. To mention a few, weight and size are kept to a minimum, air tightness is preserved, moisture resistance is required, water fording must be accomplished and varying altitude and temperature operations must be included for overall performance.

These requirements are intended to show the high quality design and components needed to meet all the specified conditions found in numerous shelter specifications today. The shelter must adapt to these loads and must withstand the constant abuse, without structural damage, for as long as its predicted life span.

Mobility aspects for these shelters must fall within the scope of MIL-M-8090D. This specification covers four types of general requirements for the mobility of military vehicles, each type being subdivided into groups according to the running gear or equipment being procured.

Type I - Mobility on improved level surfaces.

Type II - Mobility over partially improved terrain.

Type III- Mobility over highways and unimproved terrain.

Type IV - Mobility over snow and ice.

In general, Type I mobility specifies 5 to 7 1/2 mph speeds; Type II specifies 20 to 25 mph speeds, and Type III specifies 50 to 60 mph speeds on level paved highways.

4. RELATIONSHIP OF SHELTER VOLUMES, LENGTHS, AND WEIGHT

In order to facilitate determination of the probable weight of a shelter for a given length, width, and height, a trial and error approach was indicated. The results of many curves were manipulated in order to obtain the approximate curves represented by Fig. 1. For the approximation, definite shelter weight values and volumes were known, especially those at the extreme ends of the chart. The shelters under consideration were those that have been manufactured within the last three years and included width by height dimensions that ranged from 7 feet by 7 feet to 8 feet x 8 feet. The lengths of the units included those from 12 feet in length to 23 feet in length. The chart represents bare shelter weights with incorporated plenums and wiring. With so many varying characteristics for each individual shelter, such as removable panels, number of openings, distribution of equipment loads, size variation, etc., the problem of plotting such variables, with quantity relationships being non-linear, appeared impractical. The curves were, therefore, fitted to known conditions and further checked against varying volumes. The resulting curve does, in effect, represent a good approximation of weight vs. length for different height and width combinations. Fig. 1 basically considers present day foamed shelters with structural wall stiffeners an integral part of the panels.

The accompanying Table B gives the volumes obtained from external dimensions of various possible shelter sizes.

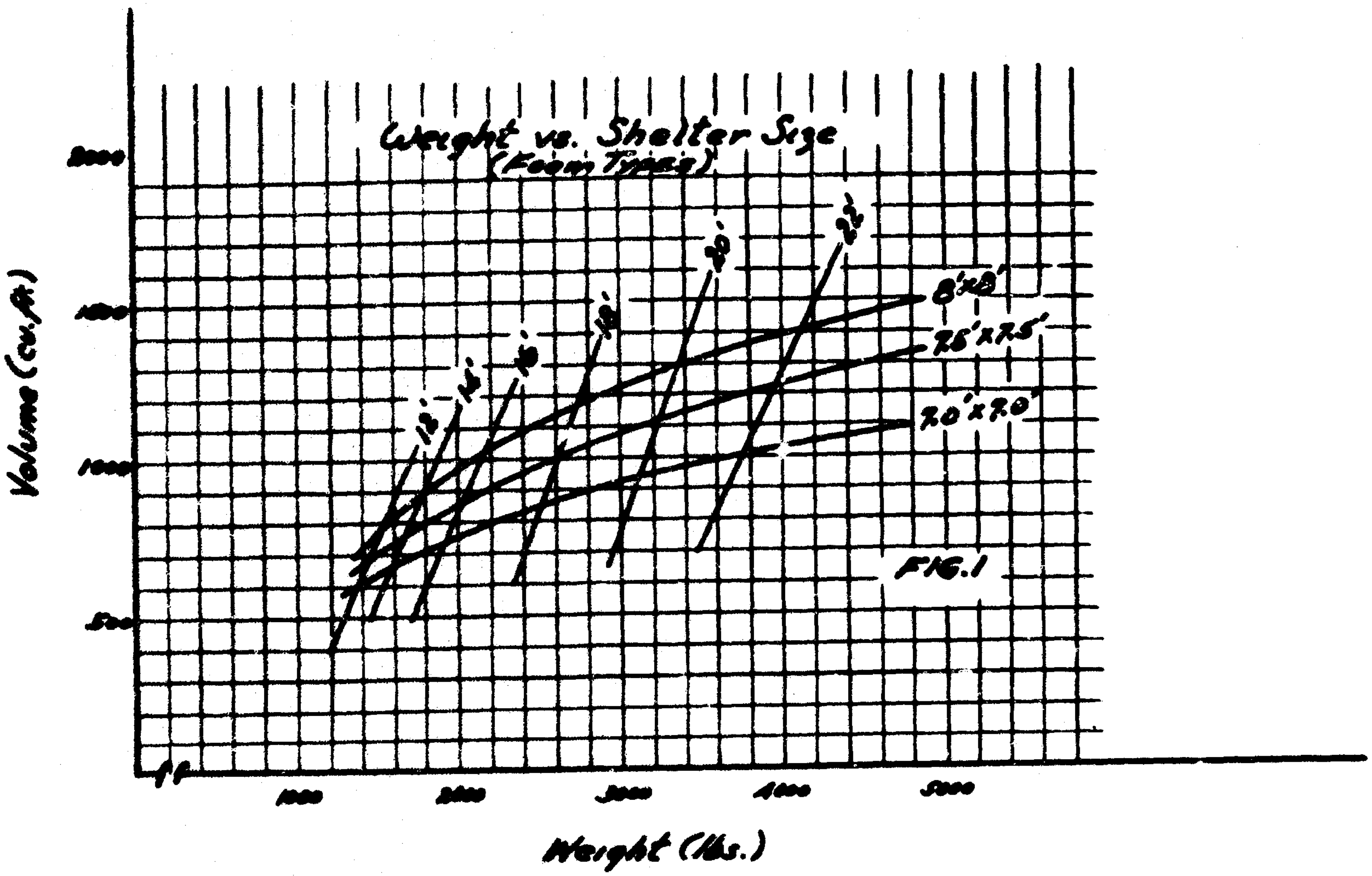
Weight vs. Shelter Size
(Foam Types)
Volume (cu. ft.)
2000
1500
1000
500
Weight (lbs.)
1000
2000
3000
4000
5000
12'
14'
16'
18'
20'
22'
8'x8'
7.5'x7.5'
7.0'x7.0'

FIG. 1

TABLE B

VOLUME (cu. ft.)

Length	8'x8'	7.5'x7.5'	7'x7'
12'	768	615	588
14'	896	788	686
16'	1024	900	784
18'	1152	1013	882
20'	1280	1125	980
22'	1408	1238	1078

As an example, to illustrate the results obtained from the graph in Fig. 1, a 7'x7'x12' shelter would weigh approximately 1390 lbs. with a total volume of 590 cu feet. Known shelter weights of the Mobile Wing facility very closely approximate these values. Again, an 8'x8'x12' shelter would weigh approximately 1500 lbs with a total volume of 770 cu feet. The weight of a 7.5'x7.5'x12' shelter can be obtained in a like manner from the configuration of the curves. The results appear adequate for close approximation within tolerable limits for system planning.

The chart should aid in determining relative shelter weights for sizes under consideration.

For an accurate and complete shelter comparative analysis, some critical observations must be made such as: what are the load carrying capacities of each unit, what is included such as wiring, plenums, jacks, etc. and also what type of shielding criteria is involved. Time did not permit such an evaluation and curves for honeycomb construction are also not indicated due to lack of definite information.

SECTION C

SANDWICH DESIGN

1. Introduction

A typical design as illustrated in Fig 2 and 2A is essentially composed of two or more materials oriented and distributed in such a manner as to provide a structural element. The core, usually a low density material, may be honeycomb, foam, balsa, etc. faced with skins made of metals or plastics. Since most military shelters of sandwich design are faced with aluminum skins, the discussions are concerned with these and cores of honeycomb and polyurethane foam only. The structural performance of such types of sandwiches is primarily dependent upon the ability of adhesives to secure a firm bond between skins and core. The choice of adhesives used should take into consideration the application to which it is to be subjected. Varying environmental and mobility conditions such as those generated by military needs, impose severe requirements that require high stable bonding strengths. Quality control in the application of adhesives requires strict adherence to the rules of cleanliness. Metallic surfaces to which bonding takes place should be thoroughly cleaned and surfaces adequately prepared to insure no entrapment of contaminants. In the use of honeycomb, as opposed to poured foam chemistry, the honeycomb cores MUST be accurately machined to within several thousandths of an inch. The machining process must be clean to avoid crumbling or shredding of the honeycomb edge which accepts the adhesive. This control over sized honeycomb must be maintained to insure complete surface bond to eliminate possibility of having areas of unbonded surfaces which affect the integrity of the sandwich. Fig. 3 illustrates good bonding practice versus a poor bonding condition. Phenolic impregnated Kraft honeycomb is more economical than foam when bought as a basic material. This fact may be offset, however, by production technique requirements.

In general, the sandwich element provides a high strength to weight ratio structure that has many uses for many applications. The strength of these sandwiches can be efficiently increased by increasing core density (cell size or foam formulation), increasing surface skin thickness, sandwich thickness or any combination of core and skin. The choice to develop strengths desired is primarily one of design.

Existing shelter structures in the field today have more or less standardized on material dimensions. The dimensions and thicknesses predominantly used have been optimized through design, test, and usage. Core densities of 2 to 4 pounds per cubic foot are common, with floor and roof sections utilizing the higher densities. Aluminum metallic skins are generally .032" thick and the sandwich is approximately 2 to 2 1/2 inches wide. Although susceptible to puncture, field repairs

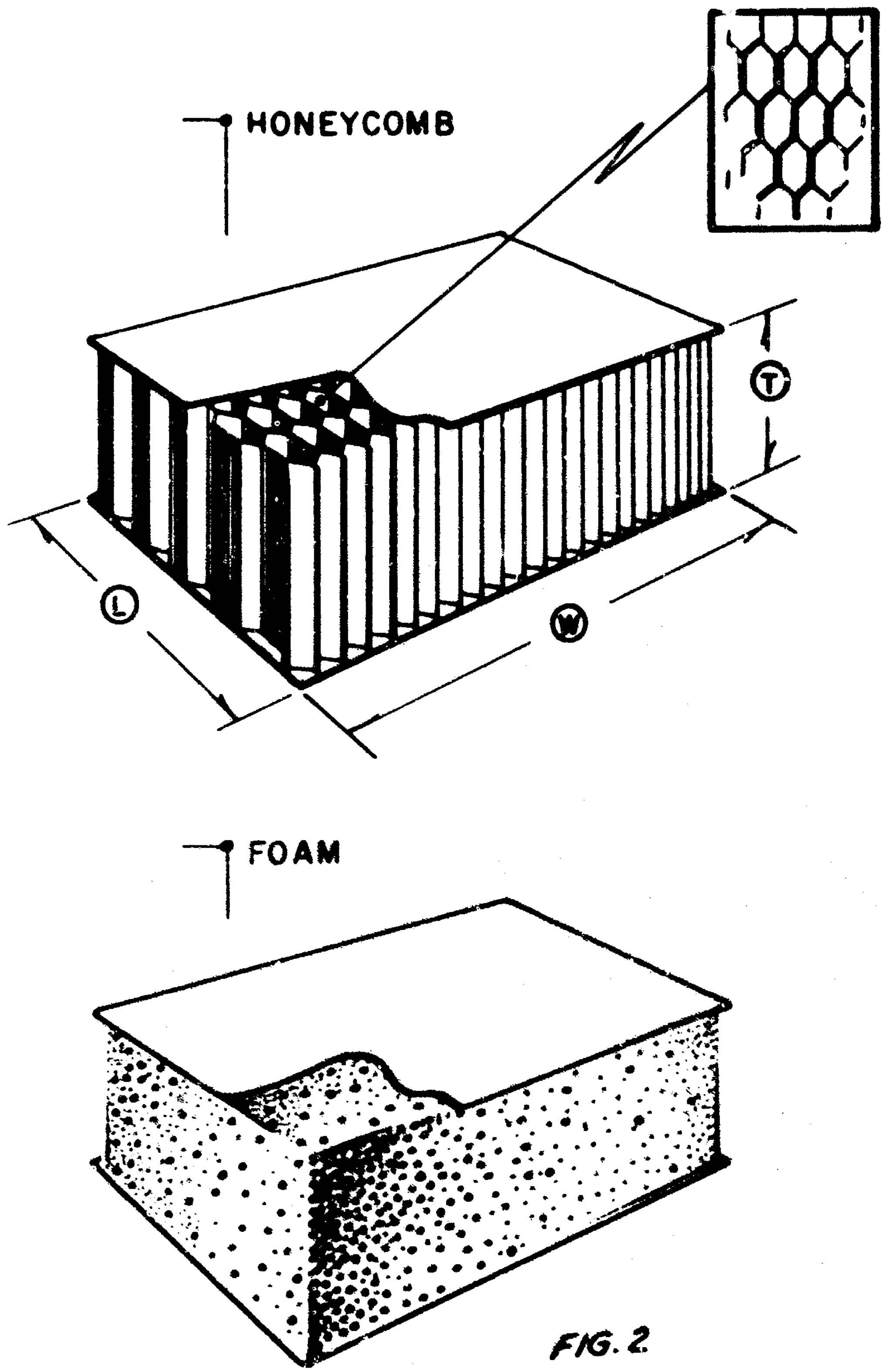

FIG. 2

PANEL CROSS-SECTIONS

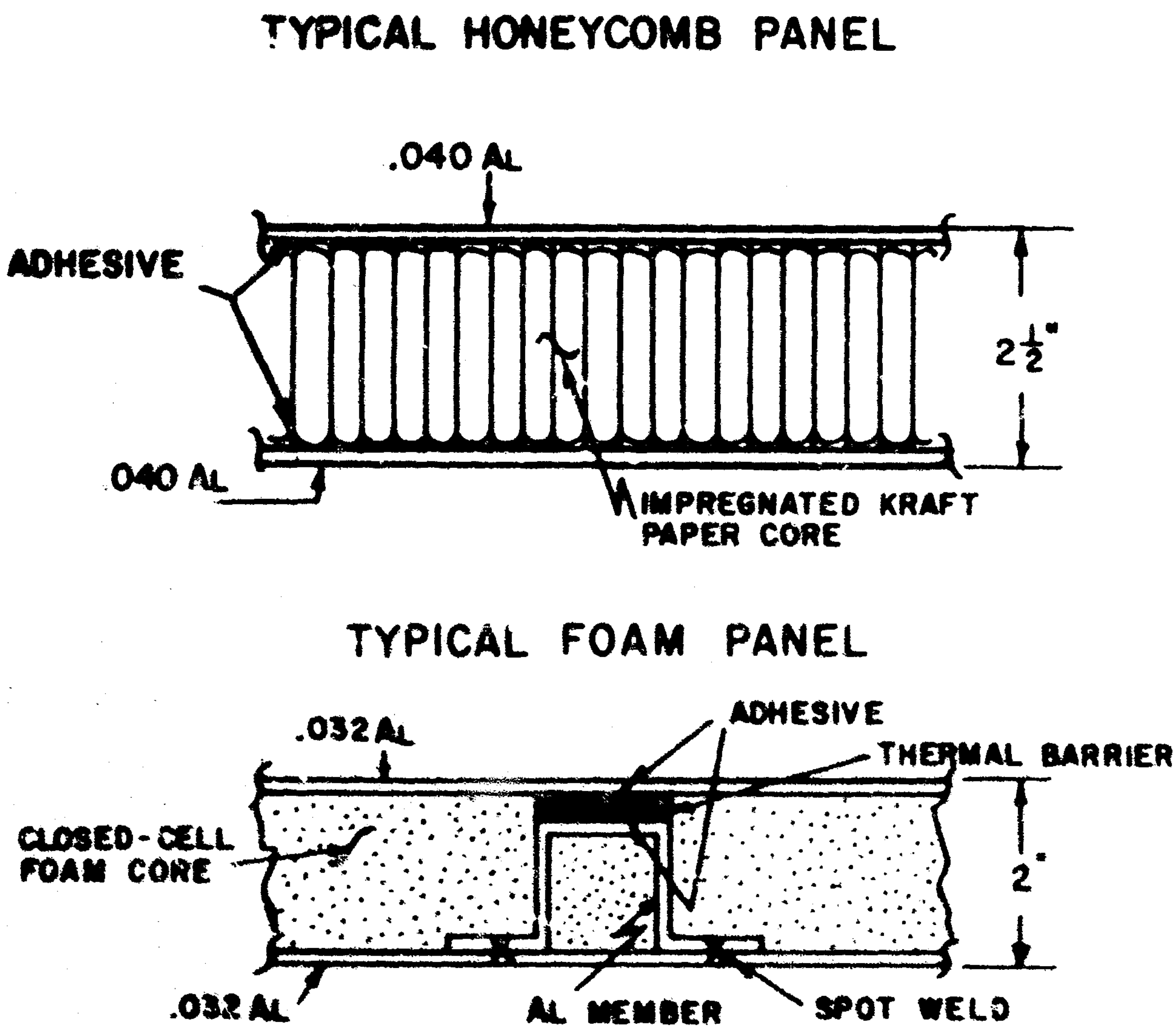

FIG. 2A

EFFECT OF BOND TYPES ON HONEYCOMB

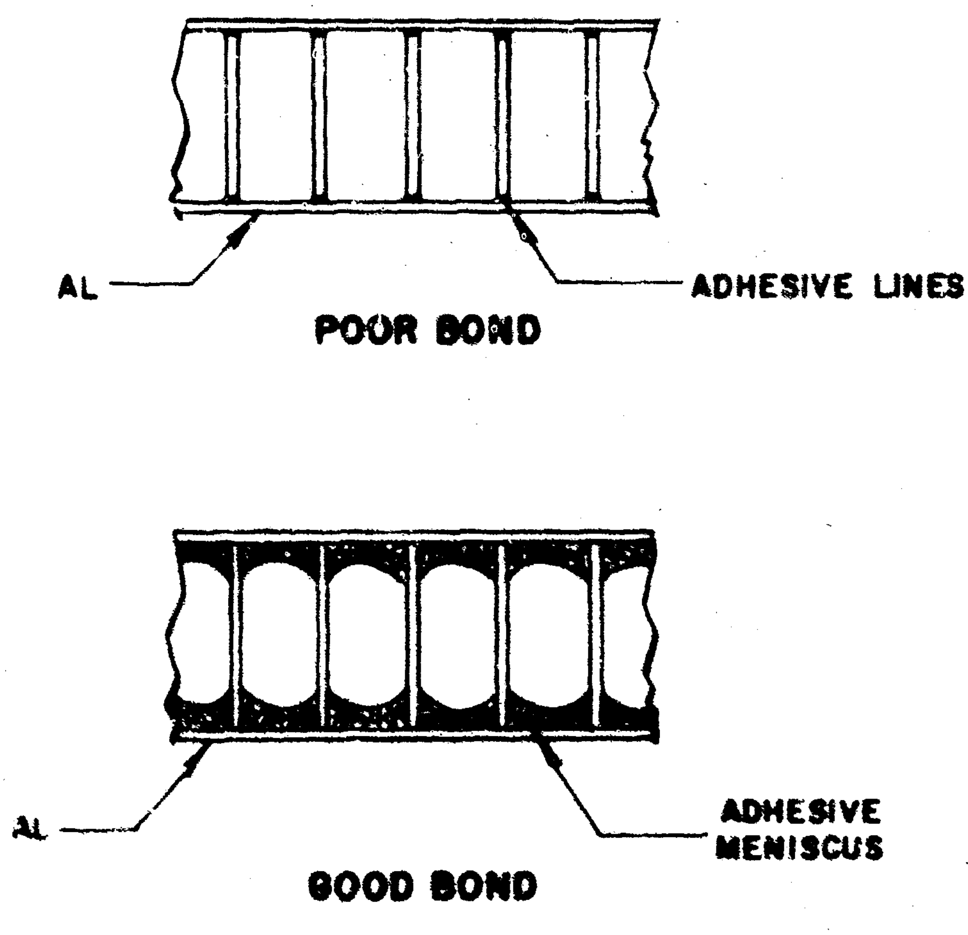

FIG. 3

can be made to take care of such occurrences. A thinner skin would puncture more frequently and a heavier skin would add to overall weight. These dimensional criteria have been established and used to acquire the strengths desired and maintain the lowest possible structure weight. No significant changes in reducing the present weight of such structures have been accomplished in the last 10 years.

a. Comparative Data: Foam vs. Honeycomb

As previously mentioned, two of the chief types of panel construction used in building lightweight mobile shelters are the foam and honeycomb sandwich designs. Each of these constructions has its advantages and disadvantages and the choice depends on a number of factors, namely:

(1) Honeycomb panels are usually thicker than foam panels for similar service.

(2) Honeycomb panels may be slightly lighter, but this advantage is often cancelled when each individual cell is filled with shredded foam to get as good heat transfer values as the foam construction permits.

(3) The bond between the metal faces and the core of a honeycomb panel is assumed heavier since the cell openings adjacent to the skins have to be well filled with adhesive, as illustrated in Fig. 3, to obtain transfer of face to core loads. Impregnated scrim cloths are used to effectively get a good bond. This adds weight and cost.

(4) As shelters require sections of increased strength by virtue of localized load concentrations, foam panels allow the use of stiffening members for this purpose. Honeycomb panel construction does not by itself permit strengthening any particular location to accommodate a concentrated load. See illustration of Fig. 4.

(5) Panels of shelters are extremely vulnerable to surface damage. In foam panels, breaks or punctures are a minor event as the bay section involved can be easily repaired on site. Punctures and breaks in honeycomb panels are more serious and if allowed to progress, the detrimental result is of major proportions. Once moisture is admitted, an entire panel may be lost and the use of the shelter may be jeopardized awaiting panel replacement. These effects are shown in Fig. 5.

VARYING CONCENTRATED LOADS

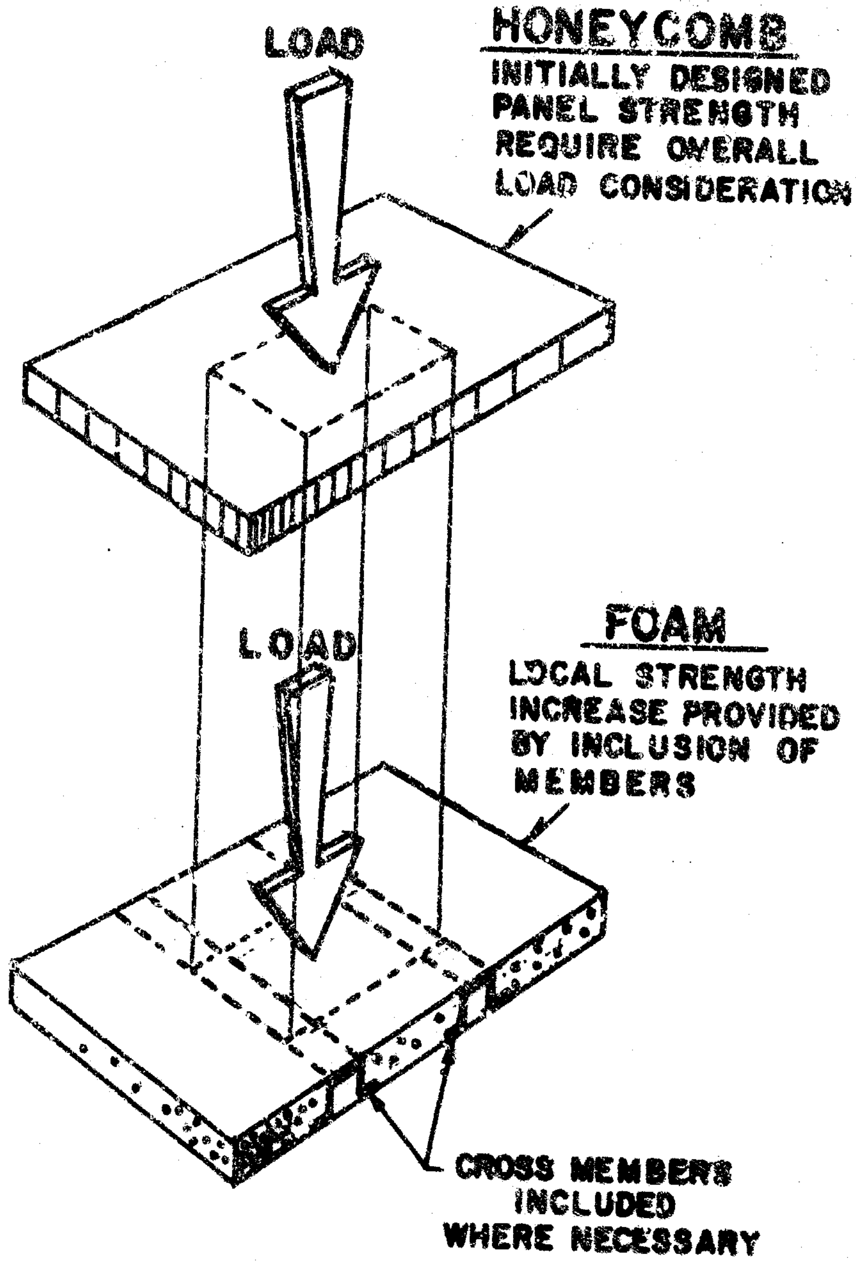

FIG. 4

DELAMINATION EFFECT
(MOISTURE ENTRANCE)

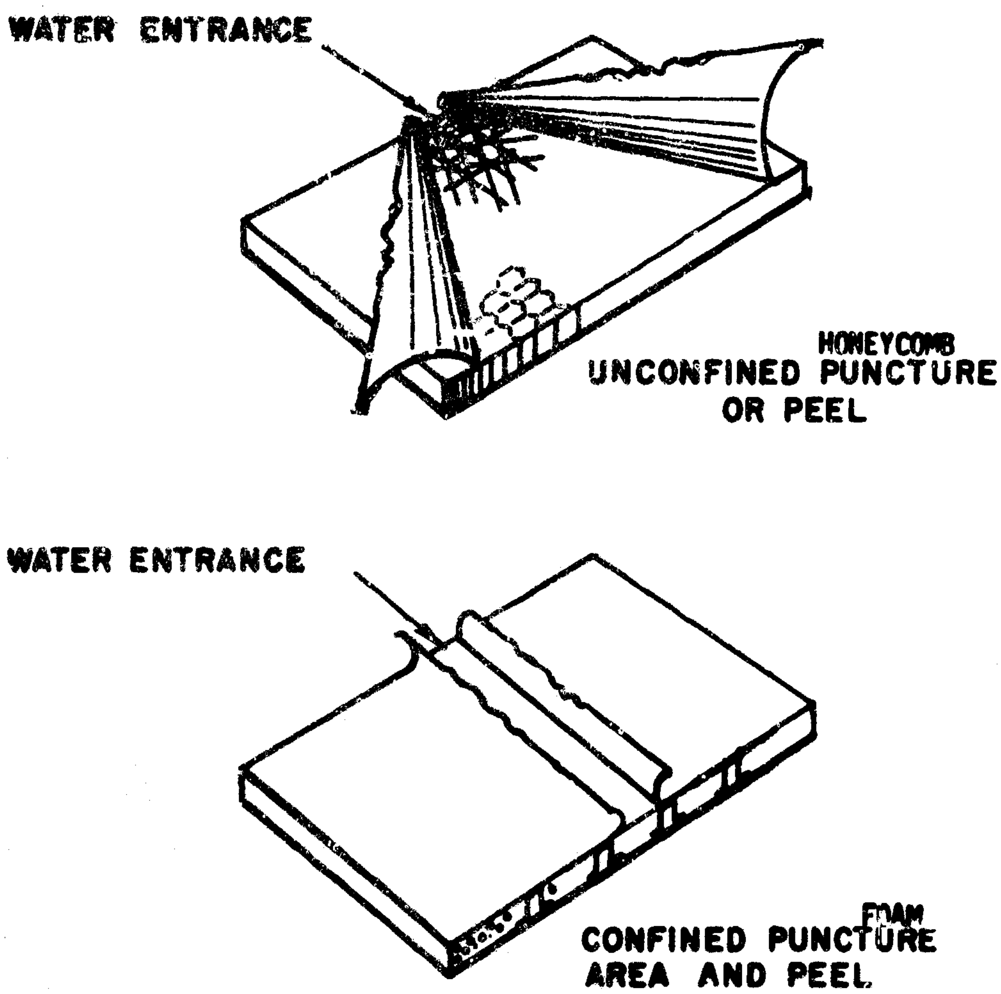

FIG. 5

(6) Honeycomb panels will accept inserts at any location; however the installation is thought to be expensive and time consuming, with the job requiring a heavy epoxy plug at each insert location. Inserts for foam panels are quickly and inexpensively installed on basic panel members which may be located anywhere in the panel as dictated by equipment lay-out. See Fig. 6 for insert setting comparison.

(7) The metal faces or skins of honeycomb panels are generally thicker than those used in foam panels to obtain support for the honey-comb cell walls.

(8) Honeycomb panels are usually stiffer than foamed panels designed for the same service.

(9) In considering costs, it is believed that honeycomb panels are more expensive than foam panels as designed for similar use. Unifor-mity of honeycomb construction is more difficult to achieve to establish a good design.

(10) Honeycomb shelters have not been time tested nor have they been through specification tests such as the S-141 and S-280 require.

(11) Honeycomb shelters' inherent fragility (g absorbing quality) requires special shock absorbing skids. Costs and transmissibility of shock and vibration flexible skids under drop test has been a factor for consideration.

(12) Foam panel construction is probably more adaptive to allow for inclusion of ballistic barriers which provide shelter with a much higher resistance to threat from fragment penetration. Using foam, this can be accomplished without sacrificing the panels ability to carry horizontal shear, a property that resists bending moments.

(13) Honeycomb panels, being stiffer and generally having heavier face materials than foamed panels, allow for impact forces to be distributed over a greater core area; thus, larger forces can be absorbed without core damage. However, if the face sheet is ruptured, moisture admission, in time, may destroy the panel unless immediate re-pair is made.

Reference is made to item (6) on inserts. The current use of epoxy plugs used in conjunction with inserts appears to be a laborious operation. The routing of the honeycomb core, the removal of the routed material through a small opening, the inclusion of the insert into the potting compound, and the time required for cure, is not an apparent simple operation. It is felt that as the requirement for inserts increases, and these are many in some instances, man hours and labor cost increases

INSERTS

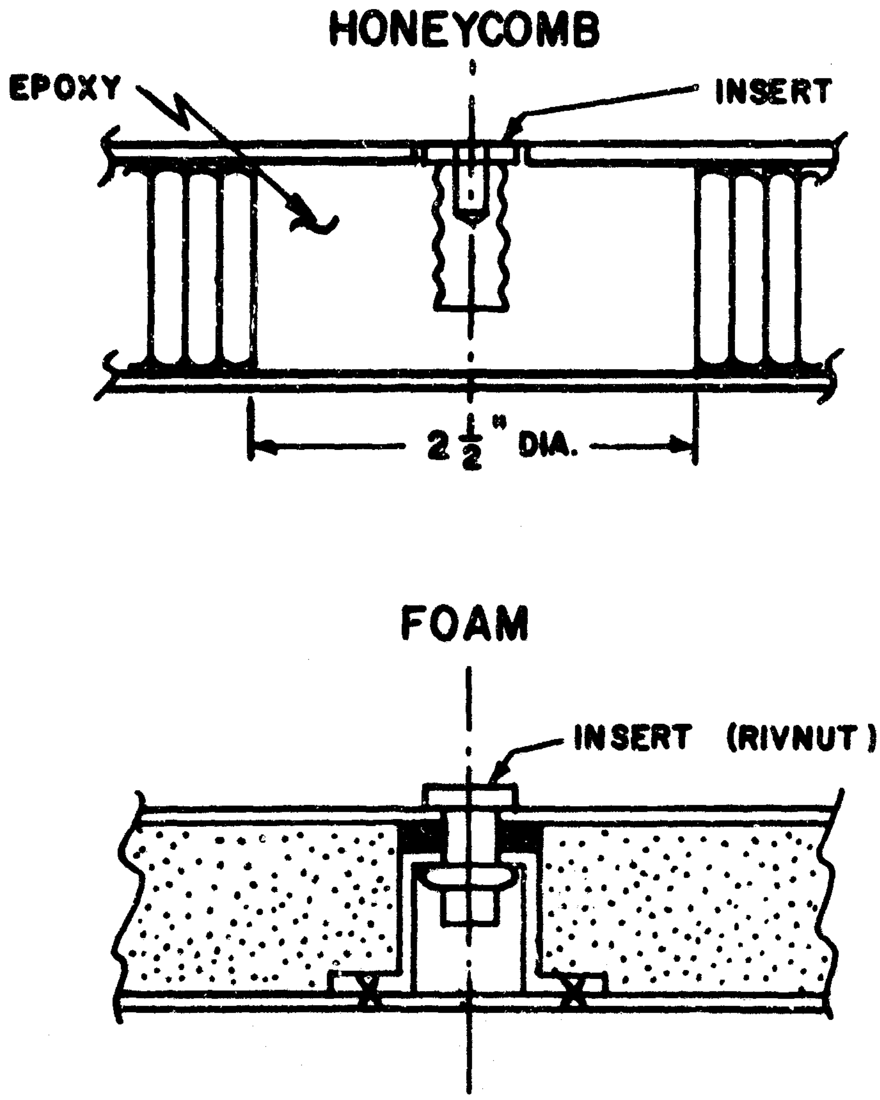

Fig. 6

could become significant. Immediate insert application can not be made in the field, since approximately 24 curing hours are required to attain full strength.

b. Panel Restraints

Basically there are certain limitations in the design of panels that deserve significant recognition. General overall shelter criteria call for lightweight structure design that implies use of lightweight panels. This criteria predicts limitations to the ruggedness of a panel and limits the structural strength of panels. Sandwich construction, as known today, offers high strength to weight ratio designs that allow for minimal structures weight to meet critical end usage requirements. It is readily noted that an increase in weight of panels by virtue of increase in core density or an increase in thickness of the panel or skins would increase both the ruggedness of the panel and its structural capability. As time progressed, and developments produced the first sandwich constructed shelters, an average wall thickness and skin gage dimensions became more or less established. These optimum dimensions were directly related in response to providing a structural capability, low coefficient of heat transmission, and lightweight characteristics to suit the military needs.

As a matter of interest, it should be pointed out that a basic limitation in regard to honeycomb panels should not be overlooked. Once such a type panel is constructed for a particular load and weight distribution, its overall dimensions and weight are therefore fixed. Then for a family of such units, a load carrying capacity should be established for the design load and any other lower loads. With inserts that can be installed at any time, shelters can be manufactured prior to actual knowledge of layout. However, once heavier loads are introduced other than that which the panels have been designed for, a problem would, in effect, exist. Thicker cores and heavier skin surfaces would be required to adapt to the increased load. Honeycomb panels imply that core thicknesses and skin surfaces would vary with varying load conditions, increasing shelter weight accordingly. If a standard shelter had to be designed to meet the highest load carrying capacity requirement of statistically determined weights, it would necessarily be of thicker walls and probably weigh more when compared to available foam shelters.

c. Response to Vibration and Shock

(1) Vibration: This section deals with perhaps the first known test of its kind performed on a complete equipment installed shelter. The shelter in question is the Image Interpretation Central, commonly referred to as the IIC and developed under an RADC sponsored contract.

The shelter, of foam-in-place construction, was subjected to a vibration criteria of 15 to 55 cycles per second through a total excursion of 0.015 inches double amplitude. The scan from 15 to 55 to 15 cps was accomplished in a period of 80 seconds, the cycling being continued for a total time of 45 minutes. The vibration fixture was mounted to the vibration equipment in the vertical axis as shown in Fig. 7. Vibration pickups were located at various points for all tests performed. The vertical, longitudinal, and lateral planes were all subjected to the vibrational inputs as indicated. The severity of this test did not affect the shelter but indicated a multitude of equipment design deficiencies which had to be subsequently corrected. Data such as this indicated the shelter performance and its high grade of stability under vibrational forces.

(2) Shock: Shock inputs to a shelter, by virtue of railroad humping, inposes approximately a 30g load upon impact and the road tests provide further information as to tynes of shock and forces that are imparted to shelters. These forces generally reach maximum crests of approximately 24 g's.

It is well to point out that honeycomb shelters are not known to have been subjected to these types of abuses.

d. Quality Control

The basic objective of a quality control program is to insure a degree of quality which is consistent with intended requirements of the user. The aspect of quality control is more significant in honeycomb than in foam.

(1) Honeycomb: To insure uniform quality in honeycomb cores, it is important that the raw Kraft paper used in their construction be of uniform quality. This material must meet rigid standards as the finished product is so largely dependent upon the uniformity of its principal material paper. A close quality control system where each batch of paper received is sampled, tested, and properly stored and conditioned, is necessary. There are a number of physical tests which can be made as the stock is received to determine if a vendor is meeting specification requirements. These tests should perhaps include the following in the physical category.

(a) Conditioning Paper: (ASTM Designation D685-44) - The strength and dimensions of Kraft papers vary considerably with the amount of moisture content they contain. It is, therefore, necessary that the untreated paper be conditioned prior to both testing and treatment. This is accomplished in conditioning chambers, where both temperatures and relative humidity can be accurately controlled. Here the paper is held until an equilibrium condition is reached before testing or using the material.

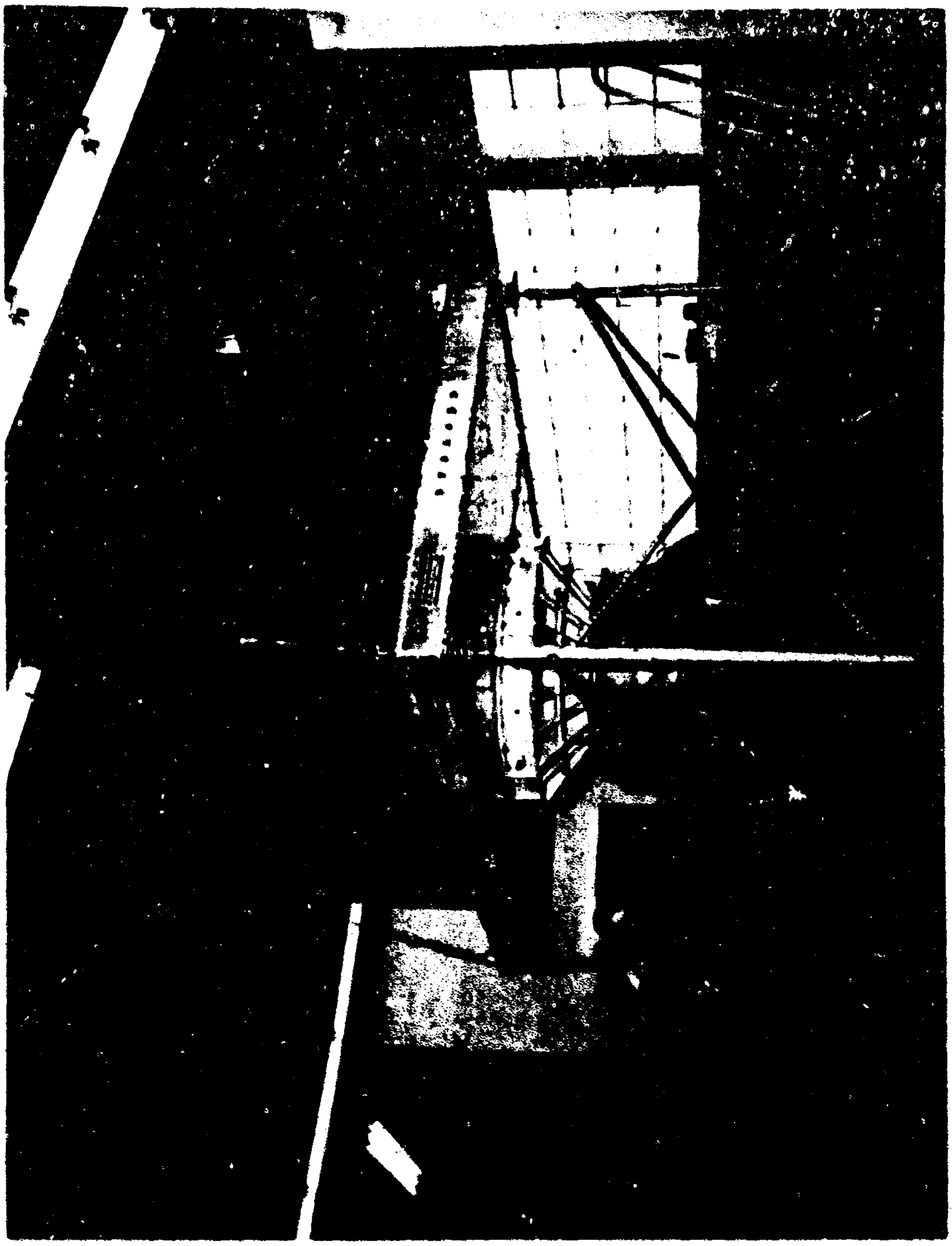

Fig. 7

(b) Paper Thickness Test (ASTM D645-58T, Method D): The uniformity of thickness in papers is very important in honeycomb core manufacture since the strength property is involved. Loss of required thickness can weaken a section considerably. The test is accomplished by use of a special type of paper micrometer employing small special discs with tension control so as not to compress the paper to any appreciable extent in taking measurements.

(c) The Mullen or Bursting Strength of Paper Test (ASTM Designation D774-46): This single test gives more information on the physical characteristics of paper than any other individual test. It will show the strength required to puncture paper in pounds per square inch, the machine and cross-machine direction of manufacture, fibre direction and fibre length. The test is performed in a special instrument called a "Mullen Tester" which may be either hand operated or motor driven. It essentially consists of a two plate clamping fixture, a rubber diaphragm which is actuated hydraulically against the paper over a 1 square inch area until the paper ruptures. A gauge in the hyraulic line measures the force in pounds at which the paper bursts. Examination of the ruptured test specimen reveals the other information listed above.

(d) The Scott Tensile Test (ASTM Designation D828-48): This test determines the tensile strength of paper. Tests are made in both the machine direction and cross-machine direction on strips of paper 1/2 inches to 2 inches wide. The specimens are clamped in jaws so that the length of paper between them is at least 5 times the width but no greater than 15 times the width. The Scott or similar testers separate the jaws at a constant rate of speed and record the force necessary to break the paper in pounds, indicated on a dial arrangement.

(e) The Elmendorf Tearing Strength Test (ASTM Designation D689-44): The Elmendorf tester determines the tearing strength of paper. This instrument measures the tearing strength of paper as force in grams to tear the paper in either the machine or cross-machine direction over a predetermined distance. The device is supplied with a cutter to start the tear, a small paper cutting board with knife and a spacer block to obtain the correct specimen size. Tables are provided in order to calculate the force in grams from the reading obtained on the instrument scale.

Information on paper testing apparatus may be made available from the Howe and Funch Company.

These tests are indicated to acquaint the reader with standards used in the paper industry. Inherently, the tolerances and controls involved in honeycomb manufacture for attainment of a good quality product are critical.

b. Foam: In quality control for foams, the foam material is generally checked for chemical composition and so marked for maximum storage time. Sample pours are tested for cell structure and compression strength. During foaming, mold temperatures and pressures are carefully monitored.

e. Noise Transmission Characteristics

Transmission loss characteristics of sandwich or foam core lightweight panels are not easily determinable nor simple. There is also very little literature available for information in the area of acoustical data related to this type of structure. The noise reduction field is however vigorously treated in many texts on most other types of panels. It is not the intent herein to elaborate on all the analytical parameters involved, but due to the basic similarity of honeycomb and foam panels a simple discussion is offered to show an apparent transmission loss relationship.

The transmission loss characteristics for these specific types of panels are not simple since the coincidence frequency (f_c) may occur in the audible bands. In the "Noise Reduction" text by Beranek, page 302, the critical frequency (lowest frequency at which wave coincidence occurs) is shown by the approximate formula

$$f_c = \frac{c^2}{2\pi d}\sqrt{\frac{2M_s}{tE}}$$

where:

C = speed of sound in air in feet per second

d = center-to-center spacing of surface sheets in feet

M_s = total surface mass of panel including the core in slugs per square feet

t = thickness of one surface sheet in feet

E = Youngs Modulus for the surface sheet material in pounds per square feet

For a given panel of 2.5 inch thickness with aluminum skins of 32 mils thickness and assuming a honeycomb or foam core of 2 pounds per cubic foot density, both structural elements behave as a single panel above their critical frequencies. The calculation below in accordance with the given equation for f_c yields approximately 123 cps and is applicable to both types of panels.

d = 2.5 in = 0.208 ft.

t = 0.032 in = 0.0027 ft.

c = 1128 ft/sec

E = 10,000,000 lb/in^2 = 1,440,000,000 $\#/Ft^2$

M_S is derived as follows:

For Aluminum Skins (density - .101 pounds per cubic inch)

$$M_{S_A} = \frac{2 \times .032 \text{ in} \times \frac{144 \text{ in}^2}{1 \text{ ft}^2} \times \frac{0.101 \text{ lb}}{\text{in}^3}}{32.2 \text{ ft/sec}^2}$$

$$= \frac{(2)\ (.032)\ (144)\ (.101)}{(32.2)} = 0.14 \frac{\text{lb-sec}^2}{\text{ft/ft}^2}$$

or 0.14 slugs/ft^2

$$M_{S_C} = \frac{0012 \frac{\text{lb}}{\text{in}^3} \times 2.5 \text{ in} \times \frac{144 \text{ in}^2}{1 \text{ ft}^2}}{32.2 \text{ ft/sec}^2}$$

$$= \frac{(.0012)(2.5)(144)}{32.2} = 0.0134 \frac{\text{lb-sec}^2}{\text{ft}^3}$$

or 0.0134 slugs/ft^2

Therefore $M_S = M_{S_A} + M_{S_C}$

$= 0.14 + 0.0134$

$= 0.1534$ slugs/ft^2

Now

$$f_c = \frac{(1128)^2}{(2)(3.14)(0.208)} \sqrt{\frac{(2)\ (0.1534)}{(0.0027)\ (1.44\times10^9)}}$$

$= (960{,}000)(0.000281)$

$= 123$ cps

This low value for (f_c) indicates that reduced transmission loss will hold through the speech band (500,1000,2000 cps Octaves). The effect of this reduced performance as a sound barrier is illustrated on page 287, Beranek, "Noise Reduction". In the region above (f_c), damping is a major contributor to any transmission loss. Control of the damping characteristics of foam materials has been readily achieved by variations in composition.

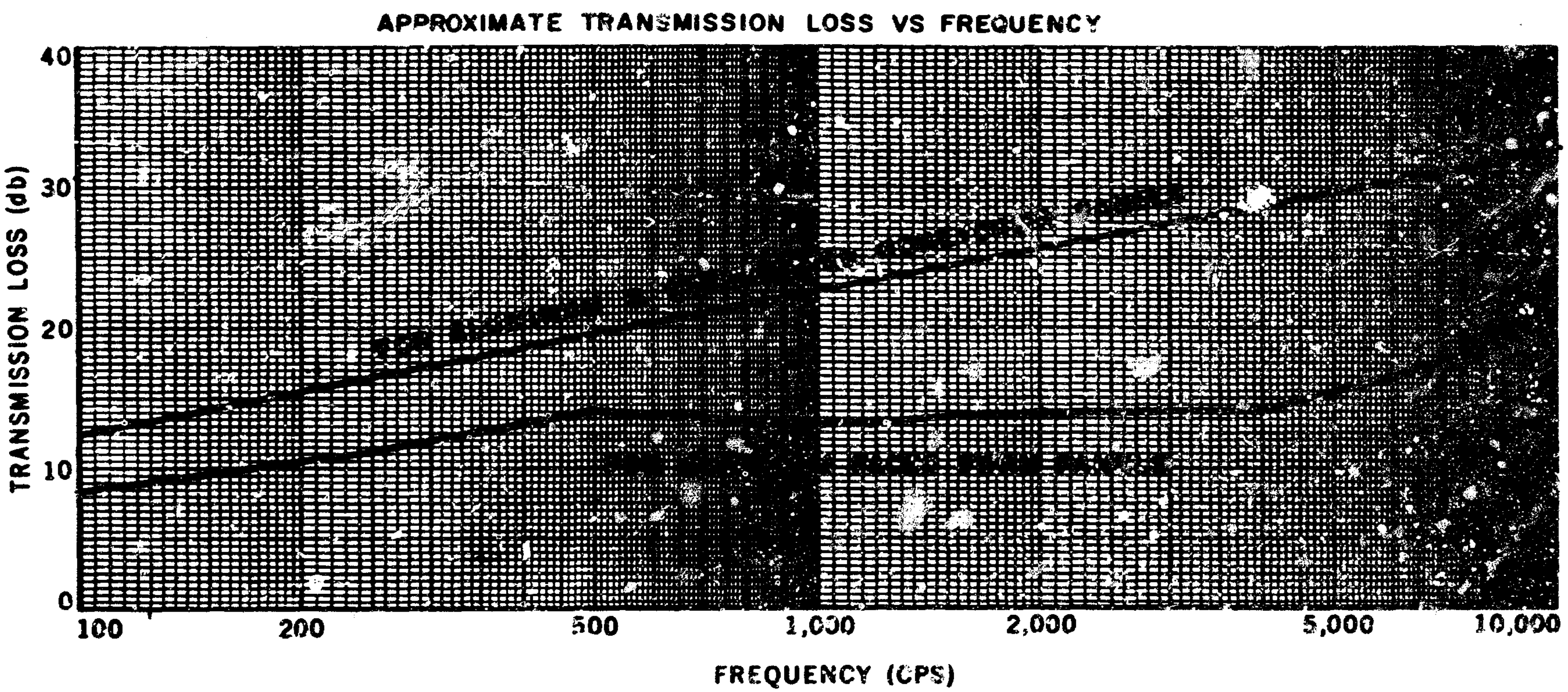

FIG. 8

UPPER CURVE (AIRCOMS TEST & TECH DATA)
LOWER CURVE (RADC TEST DATA)

The plotted data as shown in Fig. 8 was taken with a GR-1558-AP Octave band analyzer. The low and uneven losses were anticipated for such a lightweight and irregular structure (e.g., many brackets, channels, etc.). The curve given for honeycomb panels appears to be in error and is, in light of the uniform 3db per octave slope, probably somewhat imaginative. (See note below)

It c... be concluded that, with all available data, the foam panel may be designed to be more efficient as a sound barrier, but not to the extent of having high superiority. The lack of information in this area is consistent with shelter manufacturers' reluctance to submit definitive data.

The recorded data for a foam type panel is indicated below:

Octave Band Frequency	Reading Inside	Reading Outside	Loss
CPS	SPL(db)	SPL(db)	(db)
31.5	67	76	9
63	78	86	8
125	73	82	9
250	77	88	11
500	72	86	14
1000	72	85	13
2000	61	75	14
4000	59	73	14
8000	50	68	18
16000	50	53	unk
A	4	88	14
ALLPASS	82	93	11

The NR obtained is equivalent to transmission loss since special integration at close proximity to the panel was used for all reading.

NOTE: It should be understood that the curve as plotted in Figure 8 should not be compared for evaluation, since the upper honeycomb curve is the only representative data available, and as stated before, is erroneous. It is quite possible that it would fall below or close to the foam type curve. The illustration suggests only what may be expected in current data.

2. Core Properties

a. Honeycomb: Honeycomb cores designed for shelter structures are phenolic resin impregnated Kraft paper base materials. The weight of the paper and the resin content may vary depending on whether the panels are for the floor, roof, sides, ends, or doors of the shelter. In general, there are two types or grades of treated core material used, the 60 pound and the 125 pound paper, each of which may be impregnated with phenolic resin contents of 10-12% or 18-20%. Most panels utilize the higher resin content for the floor and roof panels with the heavier base paper, while the vertical panels may be either, depending upon the strength requirements and the weight limitations of the shelter.

Honeycomb core material combines strength, stiffness and insulating properties in a lightweight structure.

For property data, see Table C. (Values shown are subject to variance as literature is not consistent.)

TABLE C

PROPERTIES OF HONEYCOMB CORES

Material:		60#-20 Type 30	125#-35 Type 20
Density, lbs/cu.ft.		2.1	3.6
Compression Strength, psi)	0%R.H.	150	460
	) 50%R.H.	120	340
	)100%R.H.	36	90
Shear Strength, psi (TL plan)	0%R.H.	75	205
	) 50%R.H.	70	192
	)100%R.H.	21	74
Strength, psi (TW plan)	0%R.H.	40	120
	) 50%R.H.	375	113
	)100%R.H.	11	34
Heat transfer, K Factor)			
Btu/hr/sq.ft./F°/in)			
For 2" thick)			
1/2" empty cells)	.20-.28		
1/2" foam filled cells)	.12-.17		
Transmission Loss (db)			
Frequency (CPS)	100 - 12.5		
"	200 - 15.5		
"	500 - 19.5		
"	1000 - 22.5		

Cell Sizes (1/4, 3/8, 1/2, 3/4 and 1 inch)

REF: Aircomb Test & Tech Data; Zero Mfg. Co.

(b) Foam: Foam cores designed for panels used in shelter structures are a relatively new and versatile class of chemical compounds known as the polyurethanes. Both rigid and flexible plastic foams are available. The foamed in place construction is usually of the polyuther isocyanate rigid expandable plastic foam. The combination of properties of urethane foams makes an ideal construction material for shelter panels. The material is lightweight, stable, has excellent thermal insulation, is a fairly good adhesive and where structural strength is of importance, the higher range of densities may be used.

Panels are constructed by:

(a) Pour filling (foaming) the cavity formed by the face sheets (skins) and the supporting frame. Experience in the pre-treatment of the metal parts and the fabrication techniques of venting, foaming control, pouring and stop curing have made it possible to foam fill the largest type panels within the state-of-the-art today.

(b) Cutting slabs of rigid foam to the proper thickness, size, and shape. Then an epoxy adhesive coating is metered and sprayed onto the surfaces of the metal and foam to be joined. Finally, cured under pressure, the aluminum face sheets, supporting members, thermal barriers and frame are bonded into a light, rigid, flat and smootn surfaced panel. Foam densities from 2 pounds to 10 pounds per cubic foot are used, sometimes in the same shelter, depending upon the requirements of the function, weight, location, etc. of the various panels.

See property data Table D.

TABLE D

PROPERTIES OF FOAM CORES

Material: Polyether - Isocyanate carbon dioxide expanded

	Machine	Mix	Slab	Stock
Density, lbs/cu.ft.	2.0	4.0	2.0	4.0
Tensile Strength, psi	46	80	54	94
Compression Strength, psi				
10% deflection at R.T.	30	122	34	137
Shear Strength, psi	28	52		
Moisture Absorption, lbs/sq.ft.	.078	.067	.07	.06
Heat Transfer, K factor				
Btu/hr/sq.ft./F°/in	.120	.220	.136	.250
Stability, 20 cycles	Excellent-constant dimensions			
1 cycle - 16 hrs at 100°F, 100%R.H./2hrs at 15°F/6 hrs at R.T.				
% Closed Cells	92	90	90	89.7
Sound Absorption, NRC	.60-.70	.80-.90	.55-.65	.75-.85

Ref: Craig Systems, Inc.

D. GENERAL COMMENTS AND CONCLUSIONS

Basically, foam type shelters have been tried and tested so that performance can be predicted with reasonable assurance of meeting present day criteria. The thermal conductivity or K factors for many formulations of the polyurethane foams is equal or lower than the K factor for mineral wool-glass or rock (0.27), cotton fibre batt (0.26), wood fibre (0.25), or masonite (0.33).[1] Thus the advantages of good insulating properties, low density, combined with high load carrying capacity, and ability to be foamed in place make polyurethane foams an ideal material for sandwich core application. These structures have been efficiently used and have been built to all sizes ranging from 8 feet in length to 23 feet in length. The general height and width have been restricted to 8 feet for accommodation into cargo aircraft.

Honeycomb type shelters were procured in the past on a limited basis and at that time were observed to possess inherent deficiencies. Failures of facings near edges where concentrated loads were present often appeared. More often, the presence of moisture within panels was noticeable through increased shelter weight and panel tests. Admission of moisture into honeycomb panels must be prevented. Care and good design should be incorporated in the fabrication of edge members or the weight advantage gained through use of sandwich construction may be lost. Subjection of these shelters to the various critical environments through a time span, cannot be over emphasized, since time involved in operational use is still the best index of the quality of a honeycomb shelter. As a result of the return trend to honeycomb, it is becoming increasingly significant that these types of shelters should undergo complete structural and climatic tests. It is recommended that tests be conducted and the behavior of these units be observed and recorded so that in the event of a recurrence of old moisture problems, an unnecessary large shelter inventory need not be involved. If new techniques and materials do solve the old problems, the competition is welcomed, which may insure some new innovations in design.

The higher rigidity of honeycomb panels over foamed panels, considered an advantage, is offset in a completed shelter since foam constructed panels in a shelter offer better shock absorbing characteristics, better thermal properties, as well as slightly better noise absorption characteristics.

Your attention is invited to the appendix of this report where recent information discloses long standing honeycomb problems in aircraft, and the approach used in containing these problems. It is also important that one recognizes the level or degree of quality required for aircraft as compared to that required for shelters.

[1]Heating, ventilating and air conditioning guide 1956 Vol. 34 pp 171&172.

APPENDIX

Control of Water Entrapment in C-141 Honeycomb Panels

by L. A. Wilson, Supervisor, Quality Engineering and L. E. Meade, Manager, Composite Structures Program (condensed)

WATER ENTRY is one of the inherent problems encountered by the entire industry in the use of honeycomb. During the initial years of honeycomb use in the aircraft field, water was generally overlooked until visible external damage was observed. As a result, the airlines--for example--have a mandatory maintenance program of water-entrapment-caused repair or replacement. The airlines have continually monitored for face sheet delamination, core damage, and corrosion with subsequent repairs using fasteners or heat for baking water out. This activity has prevented any known accidents due to water entry.

Lockheed-Georgia extensively reviewed approaches to water entry control as employed in the industry. It was obvious that more advanced procedures than those currently in use were required. One of our first steps was to disregard the assumption that a honeycomb sandwich panel is sealed by its adhesive along the bond line. Use of new specifications governing the overall process of bonding and sealing honeycomb sandwich and increased testing, we believe, has made the honeycomb structures on the C-141 the most water resistant of any currently in use.

IMPROVEMENT IN WATER ENTRY CONTROL has been noticeable through the radiographic monitoring of C-141 aircraft by Lockheed-Georgia Quality Assurance. This is particularly significant since the C-141 has more honeycomb structure than any aircraft flying, and we regard in-service monitoring as very important.

By means of laboratory and field testing, Lockheed-Georgia has found that water can enter honeycomb panels by three major methods.

DAMAGE-The first and most obvious occurs when the honeycomb sandwich has been damaged by being overstressed or crushed or punctured, or by having fasteners replaced without resealing or by unintentionally scraping off the sealant. This type of problem must be controlled in the field.

WATER ENTRY SHOULD BE REGARDED AS SOMETHING TO CONTROL AND NOT TOLERATE

BREATHING-Honeycomb core, because it is sealed, contains atmospheric pressure and can cause some blow-out of sealant damage. Afterwards, at ground level, the reduced pressure in the sandwich causes moisture-laden ambient air to enter. This occurs on a cyclic basis. An added worry is having enough moisture accumulate to cause core damage by freezing when returning to high altitudes. The C-141 minimizes this problem by the use of non-perforated core, with no intercellular connections.

WICKING-Due to the use of fabric carriers in the adhesive film, some water entry has been found present only in the center of the panels. These isolated cells caused much consternation until the wicking principle was discovered. Water can enter by capillary action (wicking) along a trimmed edge and travel along a carrier fiber or strand until it reaches a point where the adhesive does not provide an entire sheath-like covering of the fiber. At this point the water enters the cell (Figures 6 and 7). All trimmed edges of panels are sealed on the C-141 to eliminate this type of water entry.

FIGURE 6

FIGURE 7

Lockheed-Georgia devoted considerable time to monitoring and evaluating the water entry rate in honeycomb test panels in order to have the ability to determine the amounts of water entrapped. Obviously the rate of entry is variable, depending primarily upon such factors as the damage and the degree of exposure.

The effect of gross amounts of water can be detected visually or by "coin" tapping the honeycomb skin. When these methods reveal water, a repair or replacement is usually necessary because the panel has delamination in that area (Figure 8). We do not recommend waiting until this occurs, but prefer to incorporate preventive measures.

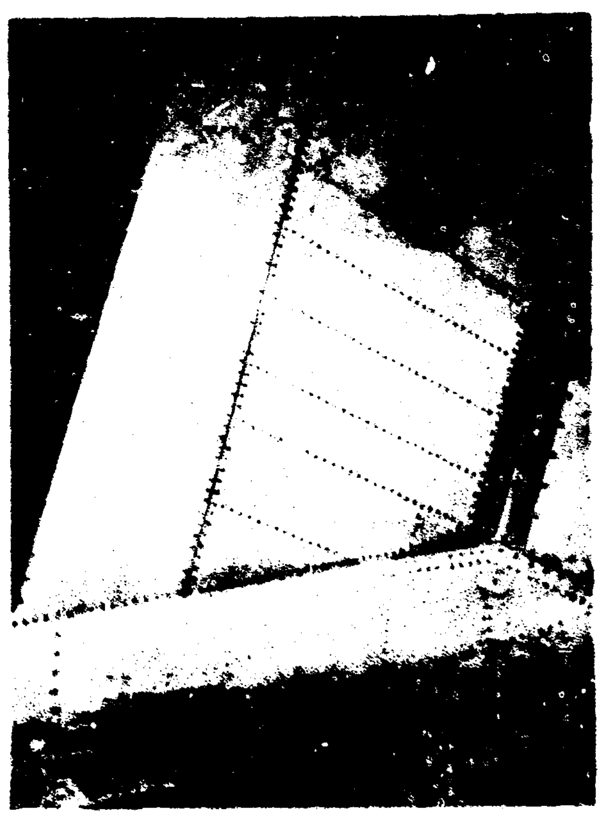

FIGURE 8

MOST LOGICAL TIME TO DETECT WATER entrapment is before core damage or delamination can occur. To detect water entrapment at this stage Lockheed uses and recommends X-ray methods. Although new methods for water detection are continually being evaluated, radiographic methods continue to remain the best means.

Due to the possibility of core damage, panel delamination, and corrosion, water entry should be regarded as something to control and not to tolerate. When entrapped water is present, steps should be taken to remove it prior to damage. Water can not be allowed to accumulate in the honeycomb panels of control surfaces even though within theoretical weight unbalance tolerances.

REPAIR. The best way to remove the water is to get it out the same way it got in, but in an accelerated manner. To do this, heat is usually employed with some enlarged exit path provided. After this is done, resealing is performed with exacting techniques. The recommended methods and techniques for repair of Lockheed-Georgia panels have been designated in T.O. 1C-141A-3. The general manual removal methods are summarized as follows:

.WATER REMOVAL PROCEDURE

Once the presence of water has been established:

1. Drill #40 holes into cavity containing water and drain water as thoroughly as possible.

2. Remove remaining moisture by heating to 150 ±10°F for 6-12 hours. A vacuum may be used to aid drying, provided care is taken not to collapse core. Low density core (2.3 to 3.4 lbs/ft^3) requires control of vacuum to 10 in Hg maximum.

3. Use radiographic inspection to determine extent of moisture removal.

4. Rebake if moisture is still present and re-examine.

5. Repair holes with rivets dipped in MIL-S-8802 sealant and seal panel in accordance with directions in T.O.1C-141A-3, paying particular attention to resealing the assembly in the area(s) of initial moisture entry.

.REPAIR OF DAMAGED AREAS

If damage to bonds and/or core results from the freezing of liquid, damage should be repaired as prescribed by T.O. 1C-141A-3. Repairs can only be made after water has been removed.

CONCLUSIONS

The inescapable fact is that honeycomb sandwich is the best material presently in use for providing the necessary weight-to-strength ratios required for modern cargo aircraft. The C-141 uses more honeycomb structure than any aircraft presently in service--over 600 individual panels representing approximately 6000 square feet of area.

Although water entry has been significantly reduced, it may still occasionally occur due to damage, the nature of honeycomb construction and use, as well as the effect of atmospheric pressure. Water entry appears to be something which can be easily controlled but should never be overlooked. By employing a system of preventive control, aircraft in service will have no significant problems as the result of water entry. Periodic monitoring by X-ray will give the necessary information to determine whether any water removal or repair may be necessary.

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13. ABSTRACT
The need for shelters today is quite apparent as one considers the complexity of systems requirements in the field of communication, data processing, and reconnaissance and intelligence. Field use of such units require exceptional strength while possessing optimum lightweight characteristics. Sandwich construction offers these characteristics. The common cores presently in use are paper honeycomb and modified polyurethane foams. Both types of cores are in use and both types of construction exhibit some poor qualities that are inherent in each. The author wishes to point out design deficiencies that should be of concern to those interested in details of such type construction. The best criteria of shelter evaluation is an established test program followed by visual observations after field usage relative to operating time.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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